# Assessing and Improving the Multifunctionality of Swiss Arable Cropping Systems

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"*The earth provides every human being's need, but not every human being's greed!*"

- Gandhi

# GENERAL INTRODUCTION

## Impacts and challenges of modern agriculture

No doubt, agricultural intensification has allowed the world population to triple over the past 70 years with the progressive integration of technology and synthetic inputs, which have led to a remarkable increase in productivity (Tilman *et al.*, 2002; Foley *et al.*, 2005). Global production has more than doubled over the last 50 years as inputs of fertilizers, water, pesticides, breeding progress and mechanization have exponentially increased. These inputs have not only contributed to support world population growth but also improved nutrition, reduced hunger and limited the conversion of natural ecosystems to agriculture (Waggoner, 1995).

However, population growth, rising per capita caloric intake, changing dietary preferences, and limited resources, are important drivers for the increasing harmful impacts of agricultural production on the environment (Smith *et al.*, 2008; Popp *et al.*, 2010). Indeed, increased use of agrochemicals, land conversion, farm expansion and specialization as well as an overall decrease in resource use efficiencies has led to decreasing biodiversity, pollution and eutrophication of water, increased greenhouse gas emissions and degrading soil quality (Vitousek *et al.*, 1997; Burney *et al.*, 2010; Geiger *et al.*, 2010; Tsiafouli *et al.*, 2015).

Intensive production does not only have adverse effects on the environment, but also compromises Earth system resilience and is therefore not sustainable in the long-term. Gerten *et al.* (2020) demonstrate that our present food system could provide a balanced diet (2,355 kcal per capita per day) for 3.4 billion people only, assuming the biogeophysical limits of the planet are not transgressed (such as biosphere integrity, freshwater use or nitrogen flows). Thus, current intensive and industrialized production systems, which are based on cost rationalization and economic growth, will never be able to *meets the needs of the present without compromising the ability to meet the needs of future generations* considering the social and environmental components of sustainability.

These concerns, together with those associated with climate change, have also reached the general public, which increasingly recognize the value of nature for human well-being (Metz and Weigel, 2010) and thus are beginning to demand more sustainable food systems and policies (e.g. several popular initiatives in Switzerland are aiming to limit or ban pesticides and protect water reserves). Thus, one of the main challenges of future agricultural systems will be to conciliate adequate productivity with improved natural resources utilization, environmental protection and social standards in a changing environment. Currently there are several alternative agricultural systems striving to reach this balance that are increasingly recognized and often supported as national and international levels, including organic agriculture, conservation agriculture, and the use of cover crops.

## Organic agriculture

In response to the rapid intensification of agriculture and raising concerns on its environmental impacts, the first milestones of the organic-biological agriculture was achieved in Europe in the 1950s following the emerging movements behind Rudolf Steiner (bio-dynamic) and Hans and Maria Müller (bio-organic). The foundation of the International Federation of Organic Agriculture Movements (IFOAM) in 1972 and the release of the first “Recommendations for international standards of biological agriculture” in 1980 definitively implemented organic production within agricultural regulations.

Organic farming is not only a way of thinking and a management strategy, but also a label production and thereafter underlie strict regulations and standards (Council of the European Union, 2018; Bio Suisse, 2020). In summary, any kind of synthetic inputs are prohibited, including pesticides, plant growth regulators, and mineral fertilizers. Moreover, the use of ionizing radiation, animal cloning and artificially induced polyploid animals or genetically modified organisms (‘GMOs’) are also strongly proscribed. Thus, organic agriculture strongly relies on natural regulation mechanisms, and attempts to close as much as possible the on-farm nutrient cycles. As a result, organic farming is based on a bundle of practices that aim to prevent as much as possible disease, pest, and weed pressure, as well as to sustain soil fertility. This includes well-regulated crop rotations (including soil regenerating ley periods), the repatriation of organic amendments (animal or green manures), the inclusion of legume crops (main and cover crops) for biological nitrogen fixation, and generally mixed-farm management linking arable and livestock production.

Organic farming is nowadays recognised as an alternative to conventional agriculture because it promotes biodiversity and soil fertility and has generally a reduced environmental impact (Mäder *et al.*, 2002; Birkhofer *et al.*, 2008; Crowder *et al.*, 2010; Gattinger *et al.*, 2012; Tuomisto *et al.*, 2012; Meier *et al.*, 2015). Despite these clear ecological benefits, organic yields are often below yields in conventional systems (de Ponti *et al.*, 2012; Seufert *et al.*, 2012; Ponisio *et al.*, 2015). This yield gap can reduce the positive environmental footprint of organic farming compared to conventional farming because more land is needed to produce the same amount of food and emissions per produced unit can then be higher than in conventional production (Tuomisto *et al.*, 2012; Meier *et al.*, 2015; Clark and Tilman, 2017).

The increased area that would be needed to fit productivity needs is a strong debate, but an extension of organic production might be possible with reductions of food waste and land used to grow non-food crops (i.e. feed for livestock), with correspondingly reduced production and consumption of animal products (Clark and Tilman, 2017; Muller et al., 2017). However, increasing organic productivity remains the main challenge, and possible solutions are limited by the self-defined and strict regulations. Mainly nitrogen availability (Ponisio *et al.*, 2015) and the use of new technologies (e.g. breeding techniques) are important bottlenecks when it comes to increasing organic yields (Haller *et al.*, 2020).

Although organic agriculture is present in 181 countries, has received increased attention in Europe, and is actively supported by governmental incentives (e.g. direct payments in Switzerland by FOAG), less than 10% of arable land is actually under certified organic production in Switzerland and only about 1.4% worldwide (Willer and Lernoud, 2019). Nevertheless, demand for organic products is constantly growing and organic products realized a market value of 97 billion US dollars worldwide (2017), with continuous growth.

**Conservation agriculture**

The economical rationalization (simplification and streamlining) of agriculture and the rapid development of heavier and high-performance machinery have led to severe threats for soils such as degradation of soil structure and increased bare fallow periods. This, together with longer drought periods or heavy precipitations, resulted in fatal erosion events, such as the impressive dust bowls during the 1930s in the prairies of Northern America. These events have made agronomists and farmers rethink basic soil tillage practices (Faulkner, 1945), which was the birth of conservation agriculture (CA) that is now recognized and supported at international level.

Conservation agriculture is based on three pillars as defined by the Food and Agriculture Organization (FAO): minimum mechanical soil disturbance, permanent soil organic cover and species diversification. In contrast to organic rules, these principles are applicable to a wide range of agricultural managements and allow a broad palette of practices for implementation. Indeed, the extensive adoption of CA principles in large farms of Northern America as well as by small-scale farmers in Southern America or Africa, and more generally its existence in all continents and all land-based agriculture, underline its broad applicability (Kassam *et al.*, 2018).

Whereas using crop rotation to increase species diversity and a permanent soil coverage (higher than 30%) are well defined, minimum soil disturbance can span from no tillage at all (no-till, direct seeding) to various form of shallow non-inversion tillage or strip-tillage. In Switzerland, conservation tillage is simply defined as soil tillage operations no deeper than 10 cm depth and is classified in three categories following decreasing tillage intensity as mulch tillage, strip tillage and no tillage.

Several studies indicate that conservation agriculture can improve agricultural sustainability (Hobbs *et al.*, 2008; Triplett and Dick, 2008). Indeed, numerous positive effects on soil quality and protection, water regulation, energy use and production costs have been observed (Holland, 2004; Scopel *et al.*, 2013; Martínez *et al.*, 2016b). Low soil disturbance and high soil coverage efficiently reduce erosion risks (Seitz *et al.*, 2018) and promote the activity and diversity of many beneficial soil organisms (Pelosi *et al.*, 2014; Säle *et al.*, 2015). Reducing tillage also reduces energy needs, as less field traffic and energy are needed to prepare soils. This results in lower labor, machinery, and fuel requirements and thus reduces overall production costs, which is one of the main aspects that contributed to the broad adoption of conservation tillage strategies.

Yields under conservation agriculture are generally slightly lower to equal than those obtained in conventional systems and depend on various factors (Pittelkow *et al.*, 2015; Knapp and van der Heijden, 2018). A meta-analysis demonstrated that similar yields could be obtained only if all three principle of CA were adopted (Pittelkow *et al.*, 2015). Moreover, yields tend to approach or exceed those after ploughing as the rainfall decreases from humid to drier regions, and thus may become an important climate-change adaptation strategy in the future. Benefits in terms of soil quality takes time and accordingly lower yields are often observed in the first years after conversion but generally then increase. Lastly, lower yields are often observed for row and tuber crops without ploughing in contrast to winter cereals that achieved similar to higher yields under CA (Martínez *et al.*, 2016a; Knapp and van der Heijden, 2018).

In 2015/16, CA was practiced on about 180 M ha of cropland, corresponding to about 12.5% of the total global cropland. CA adoption has been especially significant in South America, where about 70% of total cropland area are cultivated under this system in many countries, followed by North America and Australia. In contrast, adoption rates in Europe (5% of cropland) are much lower (Kassam *et al.*, 2018). The main reasons why CA is not widely adopted in Europe include the often more complex crop rotations (e.g. presence of ley), problems related to weed control, and delayed spring nutrient mineralization under more humid and cold climate (Soane *et al.*, 2012). Overall, the major constraints to the adoption of CA are still defined by a lack of know-how, mind-set about classical agriculture, unavailability of appropriate equipment and machines, and a lack of suitable management strategies with respect to weed and vegetation management.

Over the last decades, substantial effort has been devoted to implementing CA practices under organic production, because a combination of both strategies could have synergistic effects and further improve soil quality (Peigne *et al.*, 2007; Teasdale *et al.*, 2007; Mäder and Berner, 2012). However, a certain number of specificities limit the implementation of conservation tillage under organic management. Organic farming usually relies on intensive soil tillage to mineralize nutrients and suppress weeds in order to compensate for the lack of herbicides and synthetic fertilizers. Moreover, a thick mulch layer and non-loosened soil can hinder proper mechanical weed control operations and thus aggravate weed related problems. A meta-analysis compiling data from multiple long-term field experiments showed that weeds were consistently higher, by about 50 %, when tillage intensity was reduced (Cooper *et al.*, 2016). However, this did not always result in reduced yields. Overall, a reduction of tillage reduced yields by an average of 7.6 % relative to deep inversion tillage but varied depending on the intensity of tillage reduction. On the other hand, an increase in soil organic carbon content was observed, which indicates that reduced tillage can improve soil quality also under organic management. A synthesis of 15 years of contrasting tillage treatments revealed an increase in topsoil organic carbon, microbial biomass and activity with conversion from ploughing to reduced tillage whereas overall productivity was more or less not affected (Krauss *et al.*, 2020).

**Cover crops**

Both organic and conservation agriculture rely, for different reasons, on increased crop diversity, regulated crop rotation and improved soil fertility. In this sense, the use of cover crops offers numerous advantages. Cover crops are grown between two main crops for their multiple ecological services and are generally not harvested. Their main function is arguably to cover the soil instead of leaving bare fallow periods, and thus help protect soil against erosion, reduce the risk of surface and ground water pollution, improve soil structure, and promote soil biota (Dabney et al., 2001; Kohl et al., 2014; Schipanski et al., 2014; Blanco-Canqui et al., 2015).

Moreover, cover crops play an important role in the management of nitrogen (N) within arable cropping systems, either by preventing leaching losses (non-legume species, catch crop) (De Notaris *et al.*, 2018; Thapa *et al.*, 2018) or by providing additional N input through biological fixation (legume species, green manure) (Thorup-Kristensen *et al.*, 2003; Couëdel *et al.*, 2018). Cereal-based systems, particularly maize, benefit greatly from additional N input by legume cover crops, as shown by several studies (Miguez and Bollero, 2005; Gabriel and Quemada, 2011; Liebman *et al.*, 2012; Tosti *et al.*, 2012; Komainda *et al.*, 2017). Legume cover crops can fix more than 100 kg N $ha^{-1}$ $year^{-1}$, but it is still difficult to predict how much of this N can be effectively used by the following crop (Thorup-Kristensen *et al.*, 2003; Büchi *et al.*, 2015).

Additionally, cover crops have been shown to suppress weeds and thus have the potential to reduce tillage and herbicide use, especially if cover crops can be easily managed before the main crop is planted (Dorn et al., 2015). In general, weeds are successfully suppressed during the cover cropping period if sufficient biomass is produced (Amosse *et al.*, 2015) but effects in the next crop are variable and depend on management history and initial weed pressure (Osipitan et al., 2019; Reimer et al., 2019).

Cover crops can also be seen as a carbon source and could contribute to increased soil organic carbon and overall soil fertility. Even if contrasting and variable, a generally positive impact on C accumulation in soils was associated with the growth and incorporation of cover crop biomass if applied over a longer period of time (Poeplau and Don, 2015; Kaye and Quemada, 2017). This, together with lower fertilizer use after legume cover crops, could contribute to climate mitigation, whereas improved soil water retention, reduced vulnerability to erosion and retention of nitrogen could contribute to climate change adaptation (Kaye and Quemada, 2017).

All these benefits have been extensively described, as well as the importance of direct cover crop management, e.g. sowing and termination date or termination techniques (Thorup-Kristensen and Dresboll, 2010; Alonso-Ayuso et al., 2014; Radicetti et al., 2016; Osipitan et al., 2019). Therefore, cover crops are often recommended as a valuable practice to develop more sustainable cropping systems. Conversely, there is still poor adoption by farmers at a larger scale (Panagos et al., 2015; Seifert et al., 2018), even if various national and regional incentives have recently initiated a positive trend and higher integration of cover crops into rotations (Storr et al., 2019). Sowing cover crops incurs additional costs and labor, thus one key aspect to increase the attractiveness of growing cover crops would be to improve the return on invest for farmers by optimizing cover crop based systems in order to increase profitability (Gabriel *et al.*, 2013). This can be achieved either by reducing synthetic inputs and energy use (e.g. fertilizers, pesticides, fuel for tillage) or by significantly increasing yield, also called ecological intensification (Roesch-McNally et al., 2017). Few studies have investigated to which extent cover crop based agro-ecosystem perform within defined cropping systems (Wittwer *et al.*, 2017). Optimizing cover cropping by finding appropriate cover crops in combination with the right set of other cropping practices (e.g. tillage, fertilization, termination and sowing technics) will permit their wider adoption.

**Ecological intensification**

Instead of converting the whole production to a new system, such as a conversion to organic or no tillage management, the more general concept of ecological intensification has gained in importance over the last decades. A simple definition of ecological intensification was given by Cassman (1999) as a further increase of productivity with less negative environmental impacts to meet future food demand. However, the concept evolved to a more holistic approach that "*entails the environmentally friendly replacement of anthropogenic inputs and/or enhancement of crop productivity, by including regulating and supporting ecosystem services management in agricultural practices"* (Bommarco *et al.*, 2013). Thus, it relies on the understanding of the relationship between natural processes, their interactions with land-use and potentials to make a quantifiable direct or indirect contribution to agricultural production.

An important feature of the principle behind ecological intensification is that it is not referring to a specific list of practices or a reference system, but to a general approach based on the use of the specific capacities of a given ecosystem to function. For example, the targeted improvement of soil biological traits, known to drive multiple ecosystem functions, could improve agricultural sustainability (Bender *et al.*, 2016). This could be achieved either directly through the manipulation of soil biodiversity or indirectly by implementing practices that sustain soil biological functioning and the internal regulation of nutrient cycles. Ideally, a sustainable system will maintain the right balance between external inputs and ecosystem service delivery, thus providing high productivity based on optimized internal regulatory processes and resilience of the system, reduced input needs and reduced losses (Figure 1).

This approach has also been proposed under the term "agroecology" (Wezel et al., 2014), which has gained interest in the past few years and is generally preferred over ecological intensification (negative connotation of "intensification"). Agroecology as a practice can be seen as the results of agroecology as a scientific discipline and a movement, and comprises a combination of several innovative agronomical practices and also age-old principles or techniques that have been little studied or supplanted. Several practices have been identified to improve the sustainability of agricultural production in an ecological way. Some are already well implemented, such as cultivar choice, split fertilization, drip irrigation, organic fertilization, biological pest control or conservation tillage, whereas many others are not yet broadly implemented such as intercropping, natural pesticides, semi-natural landscape elements, agroforestry or the use of bio fertilizers and recycling fertilizers (e.g. from green waste or sewage sludge).

The very limited implementation of agroecological practices in most modern agricultural systems are a clear indication that farming practices are usually based on short-term economic and regulatory factors, without much if any consideration for sustainability (Weiner and Gibson, 2017). We need to bring ecological knowledge into practice.

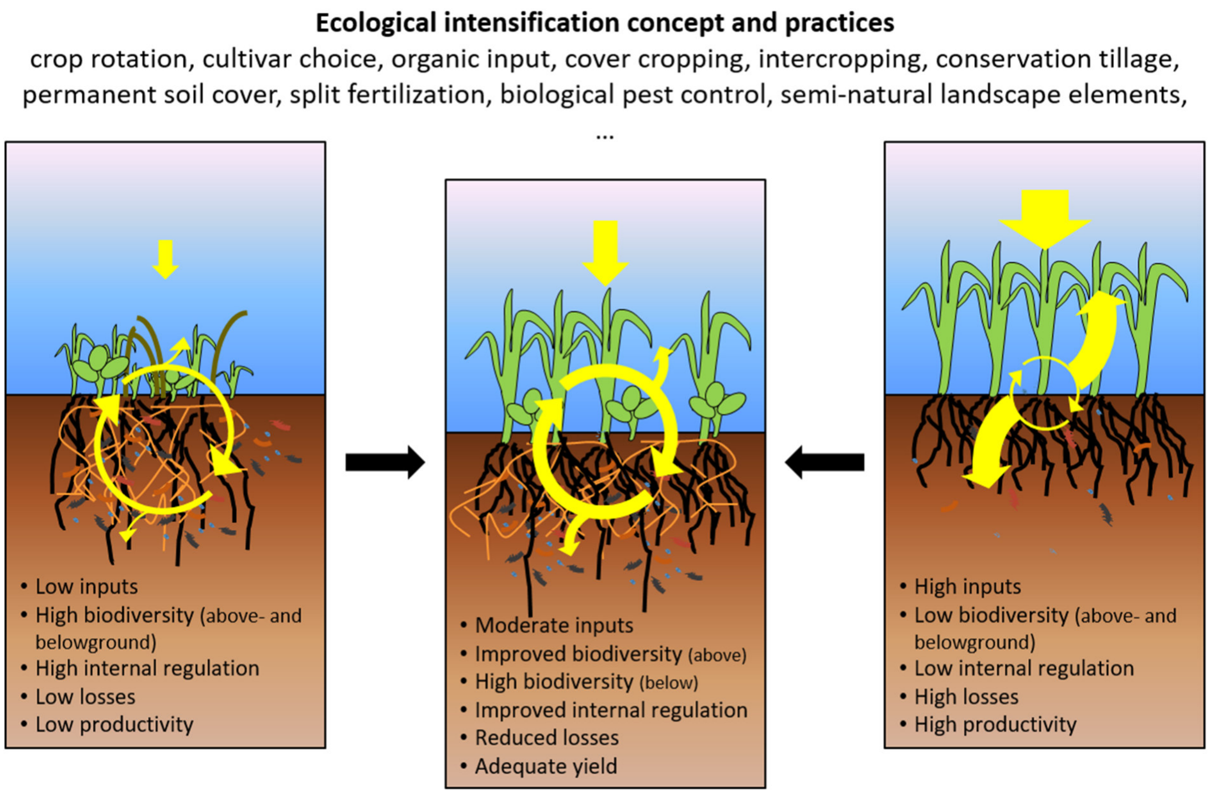


**Figure 1: Illustration of the concept of ecological intensification of agricultural cropping systems.** Adapted from (Bender *et al.*, 2016)

### Multifunctional agriculture

In contrast to productivity based modern agriculture, it is more and more recognized that agriculture does not only provide food, feed and energy products but can also provide numerous other benefits (Power, 2010). Agriculture occupies about 40% of the earth's land surface and thus has a ubiquitous impact on landscape morphology and service delivery. Thus, assessing the delivery of various services will open a potential to evaluate the overall performance of agricultural production (Philip Robertson et al., 2014).

Researchers and policy makers have attempted to accomplish this task elaborating the well-known concept of ecosystem services, or the benefits provided to humans from a given ecosystem (Costanza *et al.*, 1997). This effort has led to influential reports and frameworks that have shaped environmental policy for decades (Gómez-Baggethun *et al.*, 2010; UN General Assembly, 2015; MEA, Millennium Ecosystems Assessment, 2005). Nonetheless, properly defining and measuring aspects of ecosystem services and functions delivered by agricultural practices is a complex and challenging task and currently has not reached agricultural policies as one might wish. Recognizing and managing multiple services and disservices from agriculture beyond production needs is a major step forward to shift from a productivity-driven oriented agriculture to multifunctionality and sustainability concepts. However, proper and common understanding and defining of multifunctionality approaches is still a challenge. Indeed, in an agricultural context, different concepts distinguishing a more farm-centered multifunctional agriculture approach and the vision of ecosystem multifunctionality linked to the provision of ecosystem services have been identified. Huang *et al.* (2015) proposed an integrated conceptual framework that combines the vision of functions as agricultural activity output and functions that provide ecosystem services but underline the difficulties linked to concrete implementation in practice.

Another challenging task is to design and develop suitable methods to assess multifunctionality of agricultural systems. Some qualitative sustainability assessment models of cropping systems have been developed during the last past years, e.g. the MASC model (Sadok et al., 2009), with the difficulty to properly classify cropping systems at all (Büchi et al., 2019) and access suitable and commonly available indicators. Such models are very useful for the (re-) design of cropping systems (Peigne *et al.*, 2015) but do not allow real impact assessment. Moreover, multifunctional agriculture can be interpreted differently if looked at the cropping system scale (field, farm) (Gómez Sal and González García, 2007) or the landscape scale (Groot et al., 2007).

In the field of ecology, researchers have begun to measure and weigh a variety of ecosystem functions with the intent of quantifying the 'overall functioning of an ecosystem' (Hector and Bagchi, 2007), or the "ability of ecosystems to simultaneously provide multiple functions and services" (Manning *et al.*, 2018), in a term commonly referred to as ecosystem multifunctionality (EMF). While previous studies tended to assess single key functions, more recent studies have focused on understanding the drivers of multiple ecosystem functions simultaneously and also looked on how different factors such as biodiversity (Maestre *et al.*, 2012; Byrnes *et al.*, 2014; Wagg *et al.*, 2014; Lefcheck *et al.*, 2015; van der Plas *et al.*, 2016; Meyer *et al.*, 2018) and land management practices (Allan *et al.*, 2015) affect these multiple functions overall. However, in ecosystems where anthropogenic management plays a key role in ecosystem functions, such as agroecosystems, specific crop management practices (i.e. tillage regime, chemical and organic input sources and amounts, etc.) will most likely have a larger impact on EMF compared to species diversity. Thus knowing which management practices to follow in order to balance trade-offs between yield and environmental impacts would be a clear benefit of agriculturally-focused EMF studies (Power, 2010).

So far, the vast majority of studies assessing ecosystem multifunctionality come from natural or semi-natural ecosystems such as grasslands or forests and a systemic evaluation that takes into account the different, partly contrasting, services provided by agricultural practices is missing. In that context, cropping system long-term experiments offer a valuable opportunity to directly compare various systems and practices, under homogenous soil and climatic conditions, and offer a more detailed picture of the mechanisms and tradeoffs behind function and service delivery.

### The Farming System and Tillage experiment (FAST)

The Farming System and Tillage experiment was initiated in 2009 and is the central component of my thesis. FAST was designed as a comparative research platform to investigate the impact of important arable cropping systems on agronomical and ecological services in the long-term. Additionally, we wanted to investigate the feasibility of conservation tillage under organic management and specifically test the services provided by cover crops within and between these main arable systems.

FAST is composed of two experiments established on the same field beside each other. The first experiment started in summer 2009 (FAST I) and the second in summer 2010 (FAST II), following a staggered start design. The two main factors i) cropping systems and ii) cover crop treatments (subplot level) are arranged as a split-plot design and are randomized over four replicated blocks per experiment (Figure 2).


**Figure 2: Aerial picture of the Farming System and Tillage experiment (2017).** FAST consists of two experiments that follow a staggered start design. Four cropping systems are attributed to main plots (coloured rectangles) and the factor cover crop to subplot (visible in the bottom experiment), following a split-plot design with four blocks (replicates) per experiment.

The investigated cropping systems cover conventional, organic and conservation agriculture, which are currently the main management strategies in arable cropping. Thus, the four systems differ in terms of tillage intensity, fertilization, weed control and plant protection strategies (Figure 3) and result in conventional intensive tillage (C-IT), conventional no tillage (C-NT), organic intensive tillage (O-IT) and organic reduced tillage (O-RT) systems. Conventional treatments receive mineral fertilizer and herbicides (especially on the no-tillage plots where Glyphosate is applied). Organic treatments receive cattle slurry and no herbicides. Reduced tillage in the organic system is performed to a depth of 5-10 cm for weed control whereas no soil tillage is operated under conventional management. Every plot is divided into four subplots with four different cover crop treatments: a legume (vetch), a non-legume (mustard), a mixture of legume and non-legume and a control without cover crop (fallow).

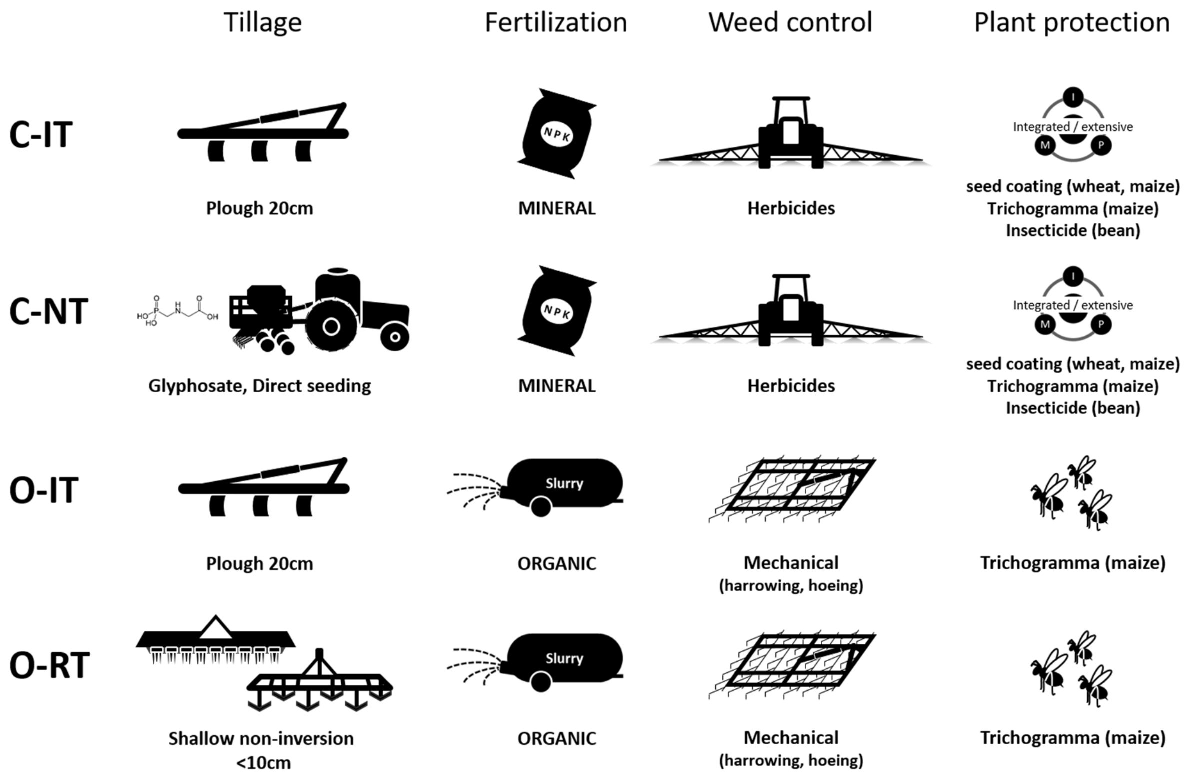


**Figure 3: Cropping system description of the Farming System and Tillage experiment.**

The same 6-year crop rotation is conducted in all systems to avoid crop specific effects between different systems but include a representative selection for Switzerland. It consist of wheat, maize, a grain-legume crop and a temporary ley (Figure 4). Cover crops were grown prior to the first winter wheat and before maize.

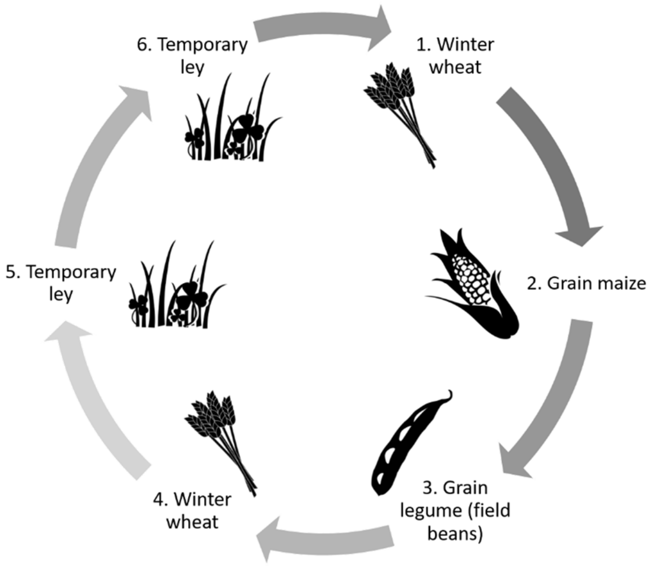


**Figure 4: The 6-year rotation of the Farming System and Tillage experiment.**

FAST has become an important research platform and has allowed multiple collaborations over the last years. Currently and in light of climate change, we investigate the resistance of the investigated cropping system to drought (Figure 5). The findings should support decision making for farmers and policy makers and contribute to the development of sustainable, productive cropping systems.

**Figure 5: Within the project RELOAD (collaboration with ETH Zurich, funded by the Mercator Stiftung), we investigate the impact of summer drought on crop yield and the potential benefits of conservation and organic agriculture in terms of climate-change adaptation** (Photo R. Wittwer).

**Thesis Outlook**

Are there possibilities to minimize negative environmental impacts of arable cropping without a decrease of yields and improve overall agroecosystem multifunctionality? The overall aim of this dissertation was to pursue that question. To do so, I made use of the Farming System and Tillage long-term field experiment to investigate ecosystem function delivery and multifunctionality of important arable cropping systems and the benefits that cover crops, and their associated ecosystem services, can achieve in terms of ecological intensification.

In Chapter 1, I analyzed a 6-year dataset from the FAST experiment and summarized 41 parameters into 14 ecosystem functions in order to assess the overall performance of the investigated systems in terms of ecosystem multifunctionality (EMF). Besides system evaluation, I evaluated the suitability of various EMF calculations and their ability to provide useful information for farmers, researchers and policy makers.

Next, I investigated more specifically the role of cover crops as an ecological tool in supporting ecological intensification of arable cropping systems. Particular emphasis was given to cover crops and their ecological functions in the agroecosystem and how these functions are expressed within different cropping systems (Chapter 2) as well as their ability to reduce anthropogenic inputs in intensive cropping systems (Chapter 3). The aim was to optimize the internal regulation of nutrients, weed control and crop diseases by integrating environmental-friendly management practices in arable cropping systems but sustain productivity.

The thesis is finally complemented by various cooperation with research groups performing additional investigations within the FAST experiment and in the frame of the FP7th EU-project OSCAR (Optimizing Subsidiary Crop Applications in Rotations). This resulted in 13 co-authored papers. These collaborations contributed to increased knowledge on the impacts of cropping systems on soil structure (Puerta *et al.*, 2018; Puerta *et al.*, 2019a), soil biota (Dennert *et al.*, 2018; Hartman *et al.*, 2018; Puerta *et al.*, 2019b), soil protection (Seitz *et al.*, 2018) and their environmental impacts (Prechsl *et al.*, 2017). Additionally, other facets of cover crops could be investigated in terms of soil properties (Papp *et al.*, 2018), phytopathological risks (Schmidt *et al.*, 2017; Walder *et al.*, 2017; Šišić *et al.*, 2018), weed control efficacy (Reimer *et al.*, 2019) and crop performance (Radicetti *et al.*, 2018).

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# CHAPTER 1

## Organic and conservation agriculture promote ecosystem multifunctionality

Wittwer, R.A., van der Heijden, M.G.A. *(Unpublished)*

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**Abstract**

It is increasingly recognized that agro-ecosystems supply multiple functions simultaneously and provide various services to humans. Assessing the overall performance of agricultural production would help to identify sustainable systems but systematic evaluations are missing. Here we evaluated the agronomic, economic and ecological performance of organic, conservation and conventional cropping systems by analyzing 41 variables and overall agro-ecosystem multifunctionality. Organic and conservation agriculture promoted ecosystem multifunctionality, especially by promoting regulating and supporting services including biodiversity, soil quality as well as climate, water and soil protection. In contrast, conventional cropping promoted provisioning services and delivered highest yield, although income was highest with organic cropping. The multifunctionality indexes showed a strong dependency upon the weighting of individual functions and revealed important trade-offs among ecosystem functions, services and cropping systems. We present an interactive online tool as a model for the evaluation and development of future cropping systems that are sustainable and productive.

**Introduction**

Global food production has more than doubled in the past 40 years. This has been achieved through use of mineral fertilizers, pesticides, breeding of new crop varieties, and other technologies of the 'Green Revolution (Tilman *et al.*, 2002; Evenson and Gollin, 2003; Foley *et al.*, 2005). However, increased use of agrochemicals, land conversion, farm expansion and specialization has a negative impact on the environment and caused biodiversity loss, pollution and eutrophication of water bodies, and reduced soil quality (Stoate *et al.*, 2009; Meier *et al.*, 2015; Tsiafouli *et al.*, 2015; Bender *et al.*, 2016). These adverse effects not only raised concerns among the scientific community but also lead to increasing criticism of intensive industrial agriculture from society. Thus, one of the main future challenges is to produce sufficient amounts of food with minimal environmental impact (Hunter *et al.*, 2017). But how can we evaluate, design and support more sustainable agricultural systems?

It is now well established that ecosystems supply multiple functions simultaneously and provide various services to humans. Among agronomists the main focus is often productivity (e.g. provisioning services) while ecologists and environmental researchers focus on the environmental impacts of agriculture. Ideally, agricultural systems should provide the desired balance of provisioning services (e.g. food production), economic services (income), regulating services (e.g. soil, water and climate protection) and supporting services (biodiversity and soil quality conservation). However, there is a lack of systemic evaluations of these contrasting services provided by agricultural practices; this is a major research gap (Seufert and Ramankutty, 2017; Tamburini *et al.*, 2020).

One of the key approaches to measure and appropriately manage agro-ecosystems is to gain a solid understanding of how farming practices influence a wide range of ecosystem functions and services and to summarize these effects in a meaningful way. In the field of ecology, a relatively new practice has emerged, in which researchers have begun to measure and weigh a variety of ecosystem functions with the intent of quantifying the ‘overall functioning of an ecosystem’ (Hector and Bagchi, 2007), or the “ability of ecosystems to simultaneously provide multiple functions and services” (Manning *et al.*, 2018), in a term commonly referred to as ecosystem multifunctionality (EMF). Here we define ecosystem functions as the biotic and abiotic processes that make up or contribute to ecosystem services either directly or indirectly.

A range of studies assessed how different factors including biodiversity (Maestre *et al.*, 2012; Byrnes *et al.*, 2014b; Wagg *et al.*, 2014; Lefcheck *et al.*, 2015; Meyer *et al.*, 2018) and land management practices (Allan *et al.*, 2015) affect individual functions and ecosystem multifunctionality. The vast majority of these studies were conducted in natural or semi-natural ecosystems such as grasslands or forests. The main focus was to understand how species diversity impacts ecosystem multifunctionality. However, this approach is still poorly developed for agro-ecosystems (Hölting *et al.*, 2019a; Garland *et al.*, 2020). In agro-ecosystems, where anthropogenic management plays a key role in determining ecosystem functioning, specific crop management practices (i.e. tillage regime, chemical and organic input sources and amounts, etc.) will most likely have a larger impact on EMF compared to plant species diversity. Thus, a next frontier is now to investigate how major cropping systems (e.g. conventional, organic and conservation agriculture) influence different ecosystem functions and ecosystem multifunctionality.

In this study, we make use of a 6-year dataset from the Farming System and Tillage (FAST) long-term experiment. We compare the agronomical, ecological and economic impacts of four important arable cropping systems (conventional intensive tillage (C-IT), conventional no tillage (C-NT), organic intensive tillage (O-IT), organic reduced tillage (O-RT)) and use the EMF approach to assess their overall performance. We focus on these specific management strategies since conservation and organic agriculture are two main alternatives to conventional management and are often promoted as more environmentally friendly practices. Organic agriculture prohibits the use of synthetic inputs (e.g. pesticides and fertilizers) and a range of studies show that organic farming enhances biodiversity and reduces environmental impacts (Mäder et al., 2002; Skinner et al., 2019; Smith et al., 2019). Conservation agriculture, in turn, is based on three main pillars: minimum mechanical soil disturbance, permanent soil cover and species diversification (FAO, 2020). Several studies indicate that conservation agriculture has positive effects on soil quality and protection, water regulation, energy use and production costs (Holland, 2004; Scopel *et al.*, 2013; Martínez *et al.*, 2016b).

To assess the overall performance of the investigated cropping systems, 41 parameters were classified into 14 ecosystem functions, grouped into supporting, regulating, provisioning and economic services and further summarized into various ecosystem multifunctionality indexes (Figure 1, Figure S2). The following ecosystem functions were assessed: plant diversity, soil diversity, soil biota abundance, soil fertility, soil structure, soil protection, water protection, climate protection, productivity, weed control, fertilizer use efficiency, income generation, work efficiency, and financial autonomy (Box 1, Table S4). Although several different frameworks for conceptualizing and categorizing these functions and services exist (Díaz *et al.*, 2015; Díaz *et al.*, 2018; TEEB, 2018; MEA, Millennium Ecosystems Assessment, 2005), we choose to group our functions into the framework of provisioning, supporting, regulating and cultural ecosystem service categories. As we analyze field data within a replicated field experiment, we substituted the cultural category with our economic variables to include a social component.

We then calculated EMF using different scenarios, weighting functions and service categories differently (e.g. scenarios where each of the 14 functions or service categories were weighted equally and scenarios giving more weight to either regulating or provisioning services). We also created an interactive web application allowing individual weighting of functions and services to evaluate how different cropping systems influence EMF using a wide range of scenarios. We also calculated diversity measures of function delivery for each cropping system following the approach of Hölting et al. (2019b) including alpha- (diversity of ecosystem function delivery) and beta- (total abundance-based dissimilarities of ecosystem function supply among all cropping systems) multifunctionality. We lastly performed a continuous threshold analysis on the alpha diversity measure in order to assess the stability of function delivery over a wide range of thresholds (Byrnes *et al.*, 2014b).

**Box1. Assessed ecosystem functions** (see methods for specific details)

| | |
|---|---|
| **Plant diversity (PlantDIV):** | aboveground plant diversity measured as weed richness. Crop diversity did not vary among the four cropping systems because each system had the same rotation. |
| **Soil biodiversity (SoilDIV):** | soil microbial richness using data for bacteria, fungi und arbuscular mycorrhiza fungi. |
| **Soil biota (SoilBIO):** | abundance of soil biota based on data for earthworms, arbuscular mycorrhiza fungi (NLFA, PLFA), bacteria (PLFA), fungi (PLFA) and microbial C. |
| **Soil fertility (SoilFERT):** | includes total nitrogen content, nutrient (P and K) availability and soil organic carbon concentration. |
| **Soil structure (SoilPHY):** | expressed as aggregate stability (mean weight diameter) and Corg/clay ratio. |
| **Soil protection (SoilPRO):** | the inverse of soil erosion risk assessed as in-situ sediment discharge. |
| **Water protection (WaterPRO):** | the inverse of water pollution risk assessed by means of Life Cycle assessment and N leaching potential measurements. |
| **Climate protection (ClimPRO):** | the inverse of air pollution risk assessed by means of Life Cycle assessment and N2O emission potential measurements. |
| **Food production (Prod):** | expressed as marketable yield (grain, forage) and yield quality (N concentration in yield). |
| **Weed control (Weed):** | the inverse of weed pressure assessed as weed cover in main crops and weed seed bank. |
| **Fertilizer Utilization Efficiency: (Fertuse)** | N, P and K utilization efficiency calculated as exported nutrients divided by applied nutrients (fertilizer). |
| **Income (Income):** | Income generation including product revenues (sales), remuneration (including subsidies) and the inverse of costs. |
| **Work efficiency (WorkEff):** | the inverse of the working load as working hours per hectares. |
| **Financial autonomy:** | the inverse of the financial dependency calculated as the amount of subsidies relative to total income. |

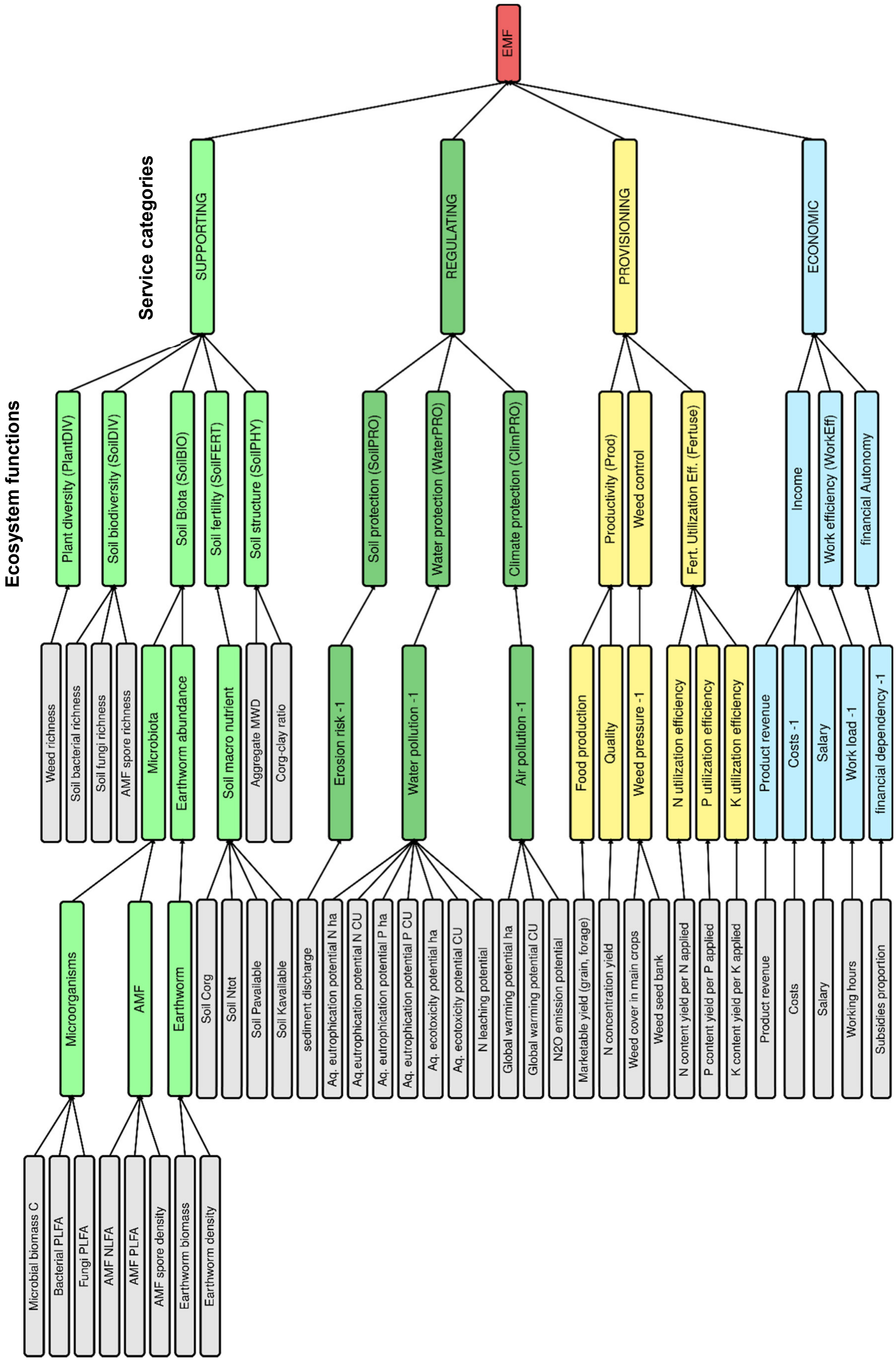


**Figure 1. Classification of the assessed parameters (grey) into ecosystem functions and service categories to assess ecosystem multifunctionality (EMF).**

**Table 1: Effects of cropping systems on selected parameters representing the 14 ecosystem functions** (full list in Table S5, C-IT conventional intensive tillage, C-NT conventional no tillage, O-IT organic intensive tillage, O-RT organic reduced tillage). Shown are absolute (mean ± standard error) and relative values compared to the conventional tilled system (% C-IT) averaged over the 6-year crop rotation. Different letters indicate significant differences between cropping systems according to pairwise comparisons on estimated marginal means. F-values for the corresponding ANOVAs and the considered random effect factors are displayed in the last two column (° $p < 0.1$, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$). Red bars indicate an undesirable and green bars a more desirable state for each parameter based on relative differences to C-IT.

| **parameter** [unit] | **C-IT** | | **C-NT** | | % C-IT | **O-IT** | | % C-IT | **O-RT** | | % C-IT | **F value** | **random factor** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **marketable yield** [t ha$^{-1}$] | **7.1** ± 0.15 | a | **6.7** ± 0.10 | ab | **-6** | **5.6** ± 0.07 | bc | **-22** | **4.7** ± 0.27 | c | **-34** | $7.08_{(3,181)}$*** | exp:block |
| **weed cover** [%] | **3.0** ± 0.8 | a | **5.7** ± 0.3 | a | **88** | **21.6** ± 1.4 | b | **613** | **31.0** ± 0.8 | c | **922** | $69.44_{(3,117)}$*** | exp:block |
| **weed richness** [nb. of spp.] | **2.0** ± 0.3 | a | **1.8** ± 0.2 | a | **-9** | **6.6** ± 0.2 | b | **234** | **6.0** ± 0.2 | b | **203** | $42.39_{(3,101)}$*** | exp:block |
| **N utilization efficiency** [kg kgN$^{-1}$] | **0.97** ± 0.02 | a | **0.95** ± 0.01 | a | **-2** | **0.65** ± 0.02 | b | **-33** | **0.57** ± 0.03 | c | **-42** | $224.59_{(3,9)}$*** | block |
| **soil aggregation** [MWD] | **923** ± 26 | a | **1075** ± 41 | b | **16** | **991** ± 38 | ab | **7** | **1136** ± 33 | c | **23** | $11.92_{(3,21)}$*** | exp:block |
| **microbial C** [mg C kg$^{-1}$ soil] | **502** ± 23 | - | **516** ± 55 | - | **3** | **512** ± 35 | - | **2** | **566** ± 22 | - | **13** | $1.51_{(3,21)}$ | exp:block |
| **Arbuscular mycorrhizal fungi** [nmol N16 1w 5] | **11.6** ± 0.6 | a | **12.8** ± 1.5 | ab | **11** | **13.2** ± 1.0 | ab | **14** | **15.5** ± 1.4 | b | **34** | $1.84_{(3,9)}$ | block |
| **earthworms** [g m$^{-2}$] | **61** ± 7.8 | a | **152** ± 7.5 | b | **150** | **112** ± 16.0 | c | **85** | **120** ± 16.2 | c | **98** | $14.51_{(3,21)}$*** | exp:block |
| **sediment discharge** [kg ha$^{-1}$ h$^{-1}$] | **346** ± 82 | a | **24** ± 4 | b | **-93** | **187** ± 31 | ab | **-46** | **73** ± 24 | b | **-79** | $4.60_{(3,21)}$* | exp:block |
| **N leaching potential** [mg N l$^{-1}$] | **24.3** ± 5.6 | a | **11.9** ± 3.9 | b | **-51** | **19.8** ± 5.1 | ab | **-19** | **13.1** ± 1.7 | b | **-46** | $2.89_{(3,9)}$° | block |
| **aquatic ecotoxicity potential** [kg 1,4-dichlorobenzene eq. ha$^{-1}$] | **708** ± 228 | a | **649** ± 225 | a | **-8** | **138** ± 38 | b | **-80** | **109** ± 26 | b | **-85** | $110.53_{(3,183)}$*** | crop |
| **global warming potential** [kg $CO_2$ eq. ha$^{-1}$] | **2457** ± 327 | a | **2194** ± 359 | b | **-11** | **1324** ± 312 | c | **-46** | **1175** ± 294 | d | **-52** | $498.33_{(3,183)}$*** | crop |
| **remuneration** [CHF h$^{-1}$] | **44** ± 2.6 | a | **57** ± 1.8 | a | **30** | **110** ± 1.5 | b | **149** | **103** ± 7.2 | b | **133** | $35.15_{(3,181)}$*** | exp:block |
| **proportion of subsidies** [%] | **0.35** ± 0.005 | a | **0.38** ± 0.004 | a | **10** | **0.37** ± 0.002 | a | **7** | **0.46** ± 0.016 | b | **33** | $5.34_{(3,181)}$** | exp:block |

## Results and discussion

### *The productivity-environmental protection dilemma*

As expected, productivity, expressed as marketable yields, significantly decreased from conventional to organic systems with highest yield in the conventional system with intensive tillage followed by the conventional no tillage system (-6%), the organic system with intensive tillage (-22%) and the organic reduced tillage system (-34%). Improved performance of the conventional systems can be explained by increased weed control and a better availability of applied nutrients (e.g. weed cover in the organic systems was 6 to 9 times higher while fertilizer utilization efficiency, especially N, was reduced) (Table 1).

The observed lower productivity of the treatments under organic and conservation agriculture is comparable to values observed in earlier meta-analyses (-6% for conservation and -19-25% for organic agriculture) (de Ponti *et al.*, 2012; Seufert *et al.*, 2012; Pittelkow *et al.*, 2015; Ponisio *et al.*, 2015; Knapp and van der Heijden, 2018). Similarly, the main barriers to successful implement conservation or organic agriculture are adequate N availablility and weed control, as highlighted in various studies (Cavigelli *et al.*, 2008; Krauss *et al.*, 2020), particularly the difficulties linked to the implementation of conservation tillage under organic management (Schipanski *et al.*, 2014b; Cooper *et al.*, 2016; Wittwer *et al.*, 2017).

In contrast to productivity, both conservation agriculture (e.g. no tillage or reduced tillage) and organic farming positively influenced most soil quality parameters. Organic farming and particularly reduced tillage intensity had a positive impact on aggregate stability (+16% for C-NT, +17% for O-IT and +23% for O-RT compared to C-IT, Table 1) (Puerta *et al.*, 2018), soil biodiversity and the abundance of macro- and microbiota. Beneficial soil biota such as earthworms and arbuscular mycorrhiza fungi performed well under organic management and conservation agriculture (Table 1, Table S5) supporting other studies (Pelosi *et al.*, 2014; Lori *et al.*, 2017; Krauss *et al.*, 2020). This confirms that improved soil management measures (crop diversity, omission of tillage, and application of organic amendments) have a positive impact on soil health (Williams *et al.*, 2020). Cropping system also affected the community composition of soil and root microbiomes within this experiment (Hartman *et al.*, 2018), with fungal communities suffering from intensive tillage (Wagg *et al.*, 2018).

Organic management and especially conservation tillage significantly reduced erosion risk (-93% for conventional no tillage, -79% for organic reduced tillage and -46% for organic tillage compared to conventional intensive tillage) and contributed greatly to soil protection in this study (Seitz *et al.*, 2018). This was explained by increased soil cover and improved aggregate stability. A recent 20-year monitoring study in Switzerland confirmed this observation and highlights the importance of conservation tillage incentives to reduce soil erosion (Prasuhn, 2020).

The organic systems had a reduced environmental impact as indicated by a 46-51% lower global warming potential (GWP) and a 80-85% reduced aquatic ecotoxicity potential (Table 1) (Prechsl *et al.*, 2017). This was particularly true when environmental impacts were calculated per unit of land but less clear when calculated per unit of food (Tuomisto *et al.*, 2012; Meier *et al.*, 2015; Clark and Tilman, 2017). We did not observe major changes in soil fertility (Corg, Ntot, available P and K, Table 1 and Table S5), which is not surprising because effects of management on these parameters are highly variable and often only become visible after long periods (Gattinger *et al.*, 2012; Leifeld *et al.*, 2013; Cooper *et al.*, 2016; Peigné *et al.*, 2018; Gubler *et al.*, 2019; Keel *et al.*, 2019).

***Effects of different cropping systems on ecosystem functions and services***

In a next step, we analyzed the effects of the four cropping systems on different ecosystem functions and service categories according to the classification in figure 1. Overall, no tillage and the organic systems significantly improved supporting and regulating services (e.g. biodiversity, soil quality, soil and environmental protection), while productivity (provisioning service) was highest in the conventional tillage system (Figure 2). However, a loss of productivity in organic systems did not necessarily translate into reduced economic performance, as highest income was attained under organic production (Figure 3 a-d, Table 1: remuneration). This results from higher product prices for organic products and higher allocated subsidies (ca. two times higher for organic systems in Switzerland). A reduction in tillage intensity also decreased costs and work load but only marginally affected general income (Table S5.).

The conventional intensive tillage system and the organic reduced tillage system were fundamentally opposed in terms of function delivery and best displayed the trade-offs between different services (Figure 2). The organic system with intensive tillage and the no tillage system showed a more balanced profile of function delivery (Figure 2). This strongly suggests that the agricultural practices implemented in these systems can improve multifunctionality and overall system performance at a satisfactory productivity level. Both conservation and organic agriculture have similar principles in terms of energy use and soil quality preservation. The use of permanent soil cover (especially in conservation agriculture, e.g. by the use of cover crops), integrated plant protection management, crop rotation and the use of organic inputs (especially in organic agriculture) seem to be beneficial and minimize the productivity-environmental protection dilemma (Cavigelli *et al.*, 2013; Seufert and Ramankutty, 2017). Particularly the implementation of cover crops has great potential to increase productivity under organic and conservation agriculture or to decrease fertilizer input without compromising yields in conventional systems (Schipanski *et al.*, 2014a; Finney and Kaye, 2017; Wittwer *et al.*, 2017; Wittwer and van der Heijden, 2020).

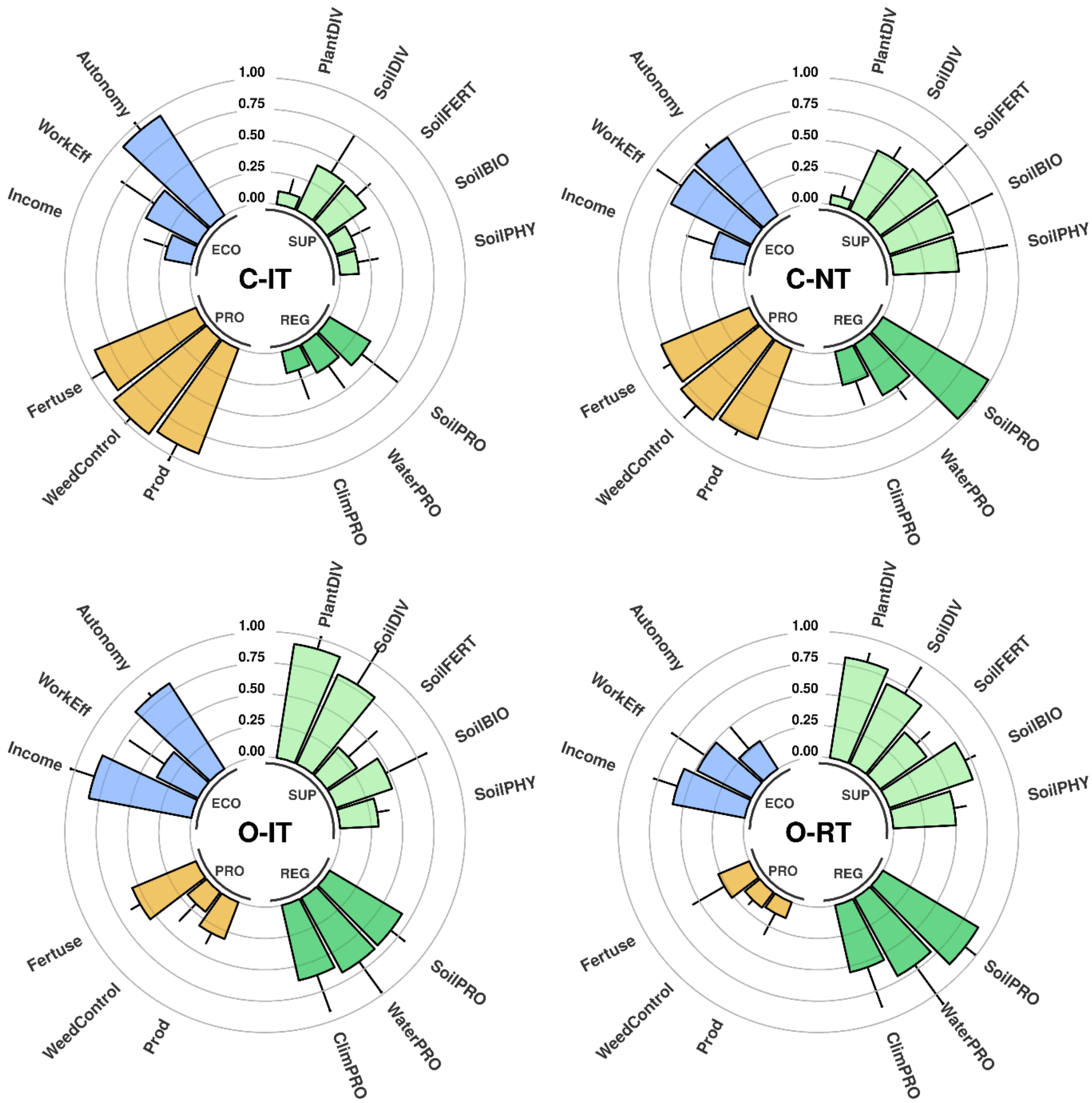


**Figure 2: Circular barplots displaying the standardized ecosystem function values for the four investigated cropping systems** (mean + 90% confidence intervals, see box1 for function descriptions / C-IT conventional intensive tillage, C-NT conventional no tillage, O-IT organic intensive tillage, O-RT organic reduced tillage). Functions are grouped into SUPporting (light green), REGulating (dark green), PROvisioning (yellow) and ECOnomic services (blue). The higher the bars the better the function is performed.

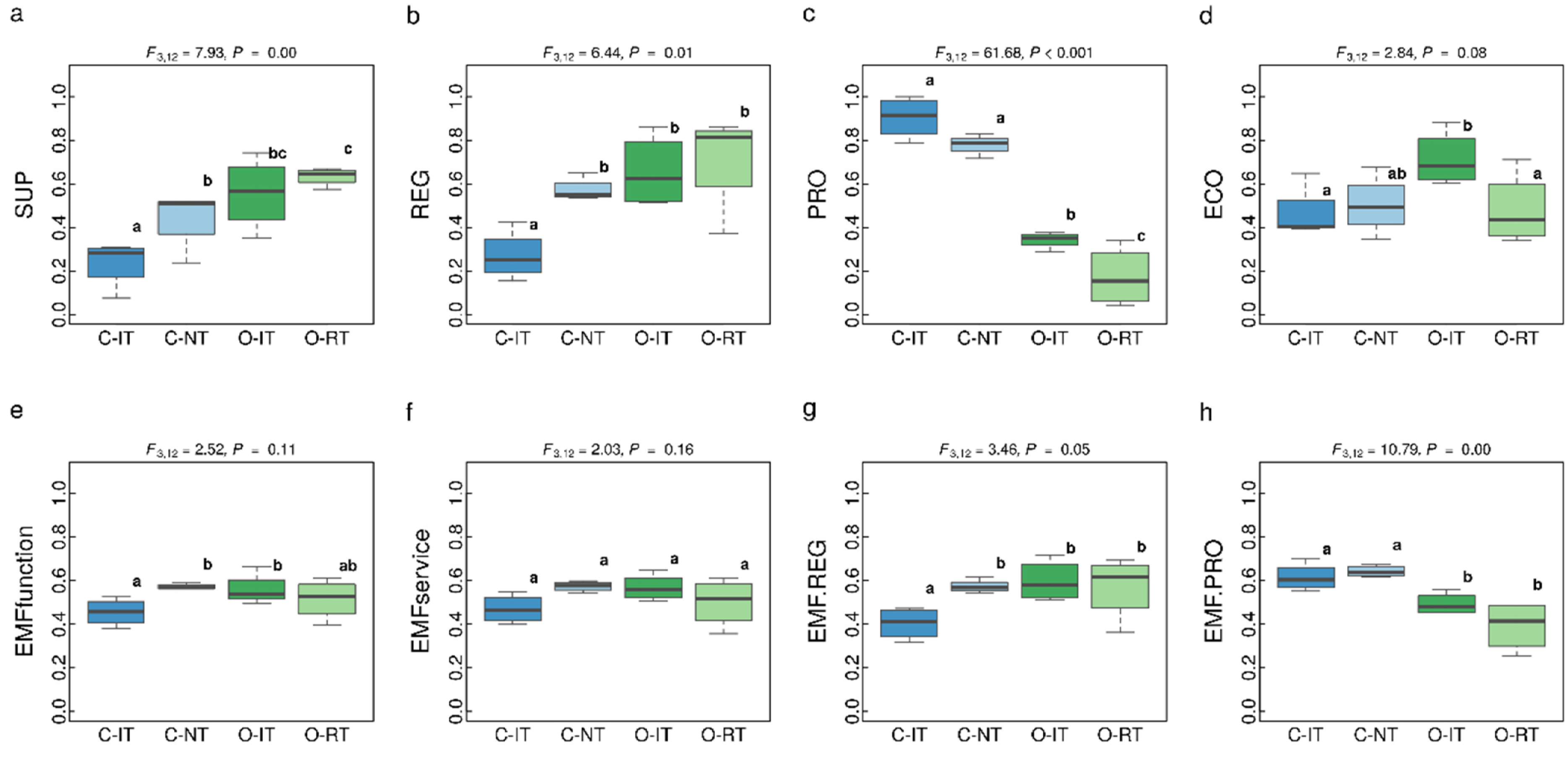


**Figure 3: a-d: Boxplots displaying Ecosystem Services delivery** (a: supporting, b: regulating, c: provisioning and d: economic services) of the four investigated cropping systems. **e-f: Cropping system effects on overall Multifunctionality** based on a scenario were all 14 ecosystem functions are equally weighed (e: EMFfunction), were all four ecosystem service categories are equally weighted (f: EMFservice), and two scenarios were regulating (g) services and provisioning (h) services have equal weight compared to the three other ecosystem services respectively. Other scenarios with different function and service categories weights can be calculated online at [https://apps.agroscope.info/sp/fast/app/emf](https://apps.agroscope.info/sp/fast/app/emf).

***Organic and conservation agriculture promote ecosystem multifunctionality***

We assessed the overall performance of the four cropping systems and determined ecosystem multifunctionality (EMF) using different approaches and scenarios (Byrnes *et al.*, 2014b; Manning *et al.*, 2018; Hölting *et al.*, 2019a). Organic agriculture and conservation agriculture promoted ecosystem multifunctionality when all 14 functions received equal weight. No tillage and organic tillage systems also tended to perform better when the four service categories were weighted equally (Figure 3e-f). In contrast, conventional systems performed best when provisioning services received most weight (50% to provisioning services) and organic systems and the no tillage system performed best when regulating services were weighed highest (50% to regulating services) (Figure 3 g-h). Thus, the EMF indexes depends strongly upon the weighing of the individual functions and service categories. To provide researchers and policy makers a tool to visualize the impact of management choice on ecosystem functions and services, we developed an interactive website that makes it possible to weigh individual functions and service categories (*https://apps.agroscope.info/sp/fast/app/emf*) and to test how different scenarios affect the multifunctionality outcome of the different cropping systems. This interactive website also visualizes that there are trade-offs between functions and between service categories and that such trade-offs are often hidden when averaged into a single multifunctionality value (Figure 3e-f).

In order to further evaluate the performance of the different cropping systems, we adapted the multiple thresholds approach from Byrnes *et al.* (2014b) and calculated how many functions were delivered above a specific threshold by the individual cropping systems . C-NT, O-IT and O-RT improved the delivery of more functions than C-IT over a wide range of thresholds (until a threshold of ca. 50%) (Figure 4a-c). Moreover, C-NT and O-IT similarly supported more functions in contrast to C-IT and O-RT, which both provided a limited number of functions at higher level (Figure 4d). As a result beta multifunctionality, which is an indication for the average dissimilarity between cropping systems, was significantly higher for C-IT and O-RT (specialized systems for a limited number of functions) and lower for C-NT and O-IT (broad-spectrum systems with more even function delivery). Note that generally not each cropping system can provide high multifunctionality and simultaneously maximize all functions (Byrnes *et al.*, 2014a; Hölting *et al.*, 2019b). This is particularly true in an agricultural context were trade-offs between different services are pronounced and food provision is the main priority. Thus, installing a balanced proportion between specialized cropping systems, providing a few functions (e.g. productivity) at high levels, and cropping systems providing diverse functions at lower levels within a given area (farm, local or regional scales) could be a strategy to achieve a balance between satisfactory yields and environmental integrity simultaneously.

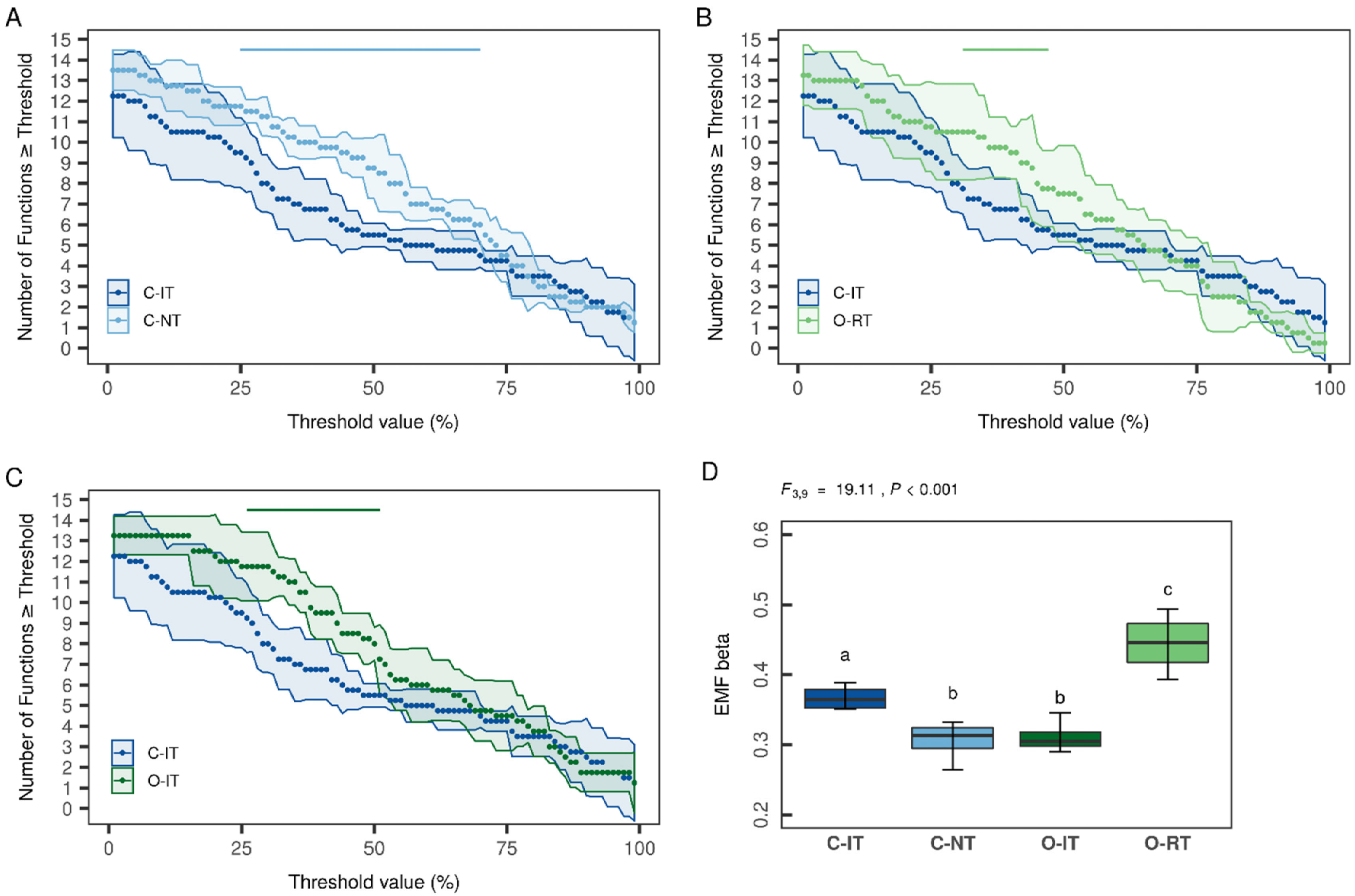


**Figure 4: Diversity measures for function delivery.** (a-c) Effect of cropping systems on the number of functions performed above a threshold (mean (points) ± confidence intervals (shades), n = 4, horizontal lines indicates significant differences to C-IT). The continuous thresholds (%) are applied on the scaled function values (0 to 1). (d) Beta-multifunctionality, calculated as the average dissimilarities of function supply between cropping systems, following the approach of Hölting et al. (2019b). The higher the value, the more specialized is function delivery (few functions at higher level and many functions at lower level). C-IT: conventional intensive tillage, C-NT: conventional no tillage, O-It: organic intensive tillage, O-RT: organic reduced tillage.

***Implications***

This study demonstrates that conservation agriculture and organic farming improve supporting and regulating services of arable cropping systems resulting in the highest multifunctionality when all functions are weighed equally. However, more intensive conventional cropping provides highest productivity, arguably the primary function of agriculture. Our analysis further shows that an increase in environmental benefits tends to be coupled with a decrease in productivity. This points to the need to clearly define which services agriculture should deliver to what extent, a goal also articulated for other ecosystem types (Allan et al. 2015; Manning et al. 2018).

The total area of arable land globally devoted to organic and no tillage systems is 1.5% and 12.5% respectively (Kassam *et al.*, 2018; Willer and Lernoud, 2019). Thus, if environmental protection and an increase in supporting and regulating services delivery, such as biodiversity conservation, mitigation of climate change or reduction of soil erosion, is a priority, the total area for organic and no-tillage cropping systems need to be substantially extended. The increased area that would be needed to fit productivity needs is strongly debated but recent studies show that an extension of organic production might be possible with reductions of food waste, a changing diet with reduced consumption of animal products and an optimized use of water and nutrients (Clark and Tilman, 2017; Muller et al., 2017).

As also indicated by our analysis for the no-tillage and the organic tillage systems, other studies suggest that specific cropping practices that contribute to improved supporting and regulating service delivery, such as the integration of cover crops (Schipanski *et al.*, 2014a; Finney and Kaye, 2017; Wittwer and van der Heijden, 2020), crop diversification (Ponisio *et al.*, 2015; Degani *et al.*, 2019; Tamburini *et al.*, 2020), reduced soil tillage (Martínez *et al.*, 2016a; Krauss *et al.*, 2020) or organic amendments (Hijbeek *et al.*, 2017; Maltas *et al.*, 2018), should be integrated in conventional cropping systems to enhance their overall performance and multifunctionality.

There is growing recognition that agriculture can provide ecosystem services other than the provision of food and feed (Swinton *et al.*, 2007; Power, 2010; Tamburini *et al.*, 2020) including biodiversity conservation, climate mitigation, or soil protection. However, it is still a challenge to monetarize and integrate such costs into product prices. Agro-environmental policies play a major role in shaping agricultural practices (Bjørkhaug and Richards, 2008). This is particularly true in Switzerland were a direct payment system (subsidies) was already introduced in the 90s to improve the ecological performance of agriculture, which include, amongst others, mandatory crop rotations, regulated nutrient balances and appropriate soil protection measures. In our analysis, the amount of considered subsidies correlated positively with the delivery of regulating services and negatively with provisioning services (Figure S4). This shows that Swiss agricultural policy supports environmental protection and compensates for yield loss.

We conclude that future cropping systems must be designed to optimize the delivery of multiple functions taking all available best practices into consideration. This because the trade-off between high productivity and environmental protection, although manageable to a certain extent, is inevitable. It is important to acknowledge that within this study we did not specifically include ‘natural’ or ‘theoretical’ thresholds above which, a system can be said to be multifunctional. The value of our analysis lies in the possibility it offers to compare different cropping systems and to identify trade-offs and key leverage options. Further development of our interactive tool, e.g. by integrating broadly applicable indicators and associated standard or limit values, could help researchers, farmers and policy makers to evaluate different management practices and to design policy instruments. Improved monitoring and evaluation of agricultural practices based on impact assessment, as proposed here, would be a next frontier to cross in the development of a sustainable agriculture.

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**Author contributions:** RW: Conceptualization, Methodology, Investigation, Formal analysis, Data curation, Visualization, Writing - original draft. MvdH: Conceptualization, Methodology, Writing - review & editing, Supervision, Project administration, Funding acquisition.

**Competing interests:** Authors declare no competing interests

**Data and materials availability:** A web application was developed along this manuscript and is available at https://apps.agroscope.info/sp/fast/app/emf.

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## Materials and Methods

### *Farming system and Tillage experiment*

This study is based on a long-term cropping system field trial entitled the “FArming System and Tillage experiment (FAST)” located at the Swiss federal agricultural research station Agroscope, Reckenholz near Zürich (latitude 47°26'N, longitude 8°31'E). The FAST experiment compares different arable farming systems, namely conventional, organic and two conservation tillage systems and has a 6-year crop rotation. The four investigated cropping systems consist of conventional cropping with intensive tillage (C-IT) or no tillage (C-NT), and organic cropping with intensive tillage (O-IT) or reduced tillage (O-RT). The four systems differ in the form of inputs (e.g. mineral versus organic fertilizers and herbicides versus mechanical weed control between conventional and organic management respectively) and tillage intensity (intensive versus conservation tillage) (Table S1).

FAST is composed of two experiments established on the same field beside each other. The first experiment started in summer 2009 (FAST I) and the second in summer 2010 (FAST II), following a staggered start design. Both comprise the following factors: cropping system and cover crop arranged in a split-plot design with four blocks per experiment. The factor cropping system was allocated to the main plots, which were each subdivided in four split-plots with the factor cover crop. The size of the main plots was 6 m x 30 m, allowing the use of standard farming equipment. The split-plot size was 3 m x 15 m (Figure S1).

The soil type at the experimental site is a calcareous Cambisol with a moderate plant available soil depth (ca. 70cm). At the start of the experiment, soil cores from the upper soil layer (0-20 depth) of each experiment were randomly collected from the experimental area for FAST I and FAST II, and soil characteristics were assessed. The soil contained on average 1.4% Corg, 23% clay, 34% silt, 43% sand, and had a pH($H_2O$) of 7.3. The long-term (1981-2010) average annual precipitation was 1054 mm and the mean annual temperature 9.4°C.

### *Crop rotation*

Before the start of each of the experiment, forage pea (*Pisum sativum* L. subsp. *arvense*) was cultivated after tillage with a mouldboard plough. The first crop rotation (2009-2015 and 2010-2016 respectively) included the following main crops: winter wheat (*Triticum aestivum* L. cv. ‘Titlis’), maize (*Zea mays* L. cv. ‘Padrino’), field bean (*Vicia faba* L. cv. ‘Fuego’), winter wheat and a 2-year grass-clover ley (‘UFA330’). Cover crops were additionally planted, within the subplot, before the first winter wheat and before maize (Wittwer *et al.*, 2017). For the main crops, coated seeds were sown in the conventional plots and untreated seeds in the organic plots. All crop residues (cover crops, maize and field bean) remained on the plots, except for winter wheat straw, which was removed from the field.

***Soil Tillage and seeding***

The intensively tilled organic and conventional plots were tilled to a depth of 20-25cm with a moldboard plough, followed by a seedbed preparation with a rotary harrow just before seeding. The conservation tillage treatment differed between the conventional and the organic systems. Under conventional management, no soil tillage operations were conducted during the entire experimental period corresponding to no tillage production (NT). The organic reduced tillage treatment consisted of non-inversion tillage (RT) to a target depth of 5cm operated with a disk harrow before wheat and thereafter with a rotary harrow at the same time as for the seedbed preparation in the IT tillage treatments. All crops were seeded directly either with a no-till cereal seeder or with a no-till single-grain seeder in the case of maize and field beans. The number, type and date of tillage operations as well as seeding dates of the crops are listed in Table S2.

***Fertilization***

Fertilization in the conventional plots was exclusively mineral and no farmyard manure or slurry was applied. Fertilization (N, P, and K) was performed in accordance with the Swiss guidelines for fertilization (Flisch *et al.*, 2009). The organic plots were fertilized with cattle slurry at a target level of 1.4 livestock unit (LU) $ha^{-1}$ (average LU for organic farms in Switzerland). The slurry was purchased from an organic farmer near the experimental site. The nutrient contents of the slurry varied between years. Consequently, the amount of nutrients applied to the crops varied slightly between experiments (Table S2). On average, the conventional plots received 92 kg $N_{tot}$, 67 kg $P_2O_5$ and 135 kg $K_2O$ per ha and year. The organic plots received 121 kg $N_{tot}$ (of which 51 kg was in in form of plant available $N\text{-}NH_4$), 46 kg $P_2O_5$ and 256 kg $K_2O$ per ha and year. Application dates and total amounts of applied nutrients for each crops are described in Supplementary Table S2 and S3.

***Weed control and Plant protection***

Weed control in the conventional plots was achieved with the use of post-emergence herbicides, whereas mechanical weed control was performed in the organic plots. In the C-NT treatment, Glyphosate was applied before seeding of the main crops. In the organic systems, a harrow was used to control weeds in winter wheat and a star cultivator was used for weed control in maize and field beans. Weed control operation dates, products and machinery are described in Supplementary Table S2.

In maize, all cropping systems were treated with Thrichogramma (*Trichogramma brassicae*) against the European corn borer (*Ostrinia nubilalis*). In field beans, Plenum WG (Pymetrozine) against black bean aphid (*Aphis fabae*) was applied in the conventional systems. Beside herbicides, no further pesticides were applied and the conventional systems thus represent more an integrated management system, which is broadly applied in Switzerland for the crops wheat, maize and field beans.

## Data collection

### *Agronomic parameters*

**Main crop yields** were assessed yearly at crop maturity by harvesting between 7.5 and 10.5 $m^2$ within the inner 2 x 10 meter of each subplot with plot-sized combine harvesters. Grain and forage yields (grass-clover) were weighted and a sub-sample was dried at 105°C for 30 hours to adjust yield to t dry matter $ha^{-1}$. Another sub-sample was dried at 60°C for 30 hours and finely ground for **nutrient** analyses (N, P, and K).

W**eed soil cover** in the main crops was visually assessed on two 1 $m^2$ frames per subplots at critical crop growth stages, few weeks after the last weed control operations. The percentage ground cover for each weed species was estimated and total **weed richness** was assessed (mean over all crops). In 2013, the **weed seed bank** was additionally determined in FAST I after wheat harvest by the seedling emergence method after Ter Heerdt et al. (1996) and adapted by Mayor and Dessaint (1998). Air-dried soil samples (0-20cm depth) were sieved at 3.15 mm and then at 0.25 mm and the remaining substrate was transferred to pots filled with steam-sterilized soil. The pots were then placed in a greenhouse with controlled light (15 hours day light), water supply and temperature (day/night, 25°C/15°C). In order to promote maximum seed germination, relevant field conditions, like reduced water supply or vernalization, were simulated in 5 phases for a total of 23 weeks of assessment. Weed germination was assessed on a weekly basis during every phase, with exception of the vernalization period (two weeks in cold room). Seedlings were identified, counted and removed mostly at early leaf development stages (cotyledons). Roots were washed in the corresponding pots to ensure that other seeds attached to roots remained in the pots.

**Fertilizer Utilization efficiencies** were calculated for the macronutrients N, P and K as the ratio between amount of harvested nutrient (nutrient concentration x yield) and total amount of nutrients applied as fertilizer. For N, atmospheric N fixation (Nfix) by legume crops (cover crops, field beans and clover) was also accounted as N input. N fixation values were not directly measured but estimated based on standard percentage Nfix (Oberson *et al.*, 2013; Anglade *et al.*, 2015; Büchi *et al.*, 2015; Wittwer *et al.*, 2017) and legume biomass.

***Economic parameters***

A full cost analysis was performed to assess the economic performance of the four cropping systems. First, **total costs** were determined including direct (seed, fertilizer, pesticide) as well as variable and indirect (land rent, machine and labor) costs. Land rent was fixed at 659 CHF per ha based on Zorn *et al.* (2015). Hourly rates for internal and external labor costs were fixed at 28 CHF and 48 CHF, respectively (Gazzarin, 2014). Machine cost were estimated based on the report of Gazzarin (2014) assuming standard machinery for Switzerland. P**roduct revenues** were calculated by multiplying marketable yield with product prices (2018). Total income was subsequently calculated by adding product revenues and direct payments (e.g. subsidies) from the government. After deduction of the total costs to the total income, the net margin was obtained, which was divided by the calculated **working hours** and added to the assumed work costs (28 CHF) to obtain the **labor remuneration**. Finally, the proportion of subsidies to total income was calculated as measure of financial **autonomy**.

***Environmental parameters***

*Soil sampling campaign*

An intensive soil sampling campaign was conducted in the fourth year of FAST I and FAST II, in 2013 and 2014 respectively. Soil samples (0-20 soil depth) were taken early march in winter wheat before any fertilization took place. Ten cores per plots were pooled to a mix sample, which was sieved using 2mm mesh after removal of large organic particles (e.g. crop residues, large roots). A fresh subsample was directly used for microbial biomass determination and another subsample was frozen at -20°C for phospholipid-derived fatty acids (PLFA) analyses. A third subsample was air-dried and used for chemical (**Corg**, **Ntot**, **P**, **K**) and texture analyses (clay, silt, sand) according to the reference methods of the Swiss Federal Institutes of Agricultural Research. Soil organic carbon was determined by addition of potassium dichromate ($K_2Cr_2O_7$), Ntot was assessed by elemental analysis and the amounts of plant available P and K were determined in $CO_2$-saturated water (Eidgenössische Forschungsanstalten, 1996).

*Soil biota analyses*

**Earthworms Abundance** was evaluated in September 2013 and 2014, a few weeks after sowing the grass-clover ley. The soil from two quadrants of 0.5m * 0.5m per main plot was collected to a depth of 20cm and a combined hand picking and formalin (0.1 %) extraction method was used to collect earthworms. Earthworms were stored in 4% formalin until counting and weighting.

**Soil microbial biomass carbon** was measured by chloroform-fumigation-extraction according to Vance *et al.* (1987). Fresh soil samples (20 g dry soil) were fumigated in duplicates with chloroform for 24 h. Organic C content was measured by infrared spectrometry after combustion at 850 °C (DIMATOC® 2000, Dimatec, Essen, Germany). Microbial biomass C was calculated according to Joergensen (1996).

**Bacterial, fungal and arbuscular mycorrhiza fungal (AMF) biomass** were estimated based on fatty acid signatures of soil samples collected from FAST II (March 2014 samples). Lipids were extracted according to Frostegård *et al.* (1991) as described by Hydbom *et al.* (2017). Bacterial biomass was estimated by summarizing the concentration of ten prokaryote specific phospholipid fatty acids (PLFAs): i15:0, i16:0, i17:0, a15:0, a17:0, cy17:0, cy19:0, 10Me16b, 10Me17:0 and 10Me18:0 (Frostegård and Bååth, 1996). PLFA 18:2ω6,9 was used as an indication for fungal biomass. The concentrations of the neutral lipid fatty acid (NLFA) 16:1ω5 and PLFA 16:1ω5 were used to estimate the abundance of arbuscular mycorrhiza fungi (AMF) (Olsson, 1999; Olsson and Johansen, 2000).

**AMF spore density and richness** were assessed on soil samples of FAST II (March 2014 samples). AMF spore extraction and identification were conducted as described in Säle *et al.* (2015). In short, AMF spores were extracted from 25g of soil samples by wet sieving and a sucrose density gradient centrifugation (Sieverding *et al.*, 1991), passed to a Petri dish, and their numbers were counted. Spores, spore clusters and sporocarps were picked without pre-selection and mounted together on microscope slides. On average, 146 (min. 102, max. 209) spores per samples were examined systematically under a microscope up to 400-fold magnification to identify all morphologically distinct AMF spore types. Morphological AMF species identification was based on all existing species descriptions and two identification manuals (Schenck and Perez, 1990; Błaszkowski, 2012). Classification was based on the Glomeromycota system of Baltruschat *et al.* (2019) and Wijayawardene *et al.* (2020).

**Bacterial and fungal diversity** was assessed as described in Hartman *et al.* (2018): Soil samples were collected in June 2013 and 2014 for FAST I and FAST II respectively. Five soil cores (at 10–20 cm depth) were collected in each plot between wheat rows, pooled and immediately frozen at − 80 °C until DNA extraction. DNA was extracted from a 300-mg soil (dry weight) subsample using the NucleoSpin Soil DNA extraction kit (Machery-Nagel GmbH & Co. KG, Düren, Germany) according to the manufacturer's instructions, except each sample was extracted twice and the supernatants pooled to maximize DNA yield. The 16S rRNA gene amplicon library was generated using the PCR primers 799F [72] and 1193R [73]. The ITS amplicon library was generated using the PCR primers fITS7 [74] and ITS4 [75]. Raw reads were processed using a custom-developed bioinformatics pipeline described in Hartman *et al.* (2018) and taxonomy assignment was done using the UNITE database (v7.0) with the RDP classifier in QIIME. In this study, we used soil bacterial and fungal richness as measure of microbiota diversity.

*Aggregate and erosion risk assessment*

Soil **aggregation** was assessed in samples collected at the end of the fourth growing season (August 2013 and 2014, after wheat harvest). Four intact soil cores (5.5 cm×20 cm) were taken from each replicate plot using a Giddings hand sampler (Giddings Machinery Co, Windsor, Colorado, USA). Each 20 cm-length core was manually cut at 6 cm, separating the top 0–6 cm from the bottom 6-20 cm. Field-moist cores were sieved at 8mm by manually crumbling along natural fracture lines in order to minimize aggregate disruption. The four cores from each plot were combined and each composite sample was air-dried and stored at room temperature. Air-dried soil was wet-sieved following Elliott (1986) to separate four aggregate size classes: large macroaggregates (LM;>2000 μm), small macroaggregates (SM; 2000–250 μm), microaggregates (mi; 250–53 μm) and silt and clay (S+C;<53 μm) as described in Puerta *et al.* (2018). Mean weight diameter (MWD), used as a measure of aggregate stability, was calculated for the top soil samples (0-6cm) using the proportional abundance of each aggregate fraction and the mean diameter of each size class.

In-situ **erosion** assessments were performed once in FAST I and II: (1) in August 2014 on fallow land one week after harvesting winter wheat in FAST II, and (2) in June 2017 in a maize stand (growth-stage BBCH 35 stem elongation) in FAST I. The determination of sediment delivery was performed using a portable rainfall simulator with runoff plots (ROPs, 0.4 m× 0.4 m). The full method is described in Seitz *et al.* (2018) but shortly a heavy rainfall event (60 mm $h^{-1}$) was simulated for 30 min on every ROP with a mean kinetic energy expenditure of 475 J $m^{-2}$ $h^{-1}$ with a portable, single nozzle rainfall simulator generating a standardized rain spectrum under a protective tent. Runoff and sediment delivery were collected in 2-l bottles and filtrated on fiberglass filters. Sediment was oven-dried (40 °C) before weighing.

*N leaching and $N_2O$ emission*

I In 2014, intact soil cores were excavated after wheat harvest from FAST II to assess potential $N_2O$ emissions and leaching losses. Soil cores were collected using HDPE tubes inserted into a steel sampler following Knacker *et al.* (2004). Two intact soil cores (40 cm height; 17 cm diameter) were extracted per mainplot and transferred into the greenhouse in a randomized block design. The cores were maintained in the greenhouse for 1 month and all emerging seedlings were removed. Afterwards, soil cores were adjusted to field capacity by successively adding water until leachate occurred at the bottom of the soil core. Leachates were collected, weighed and stored a 4°C for later analyses of nutrient concentrations. $NO_3^-$ and $NH_4^+$, in leachates were determined using a Dionex DX500 anion chromatograph (Dionex Corporation, Sunnyvale, CA, USA) and concentration values were used as **N leaching potential**.

Next, eight seedlings of Grass (*Lolium multiflorum*, var. Morunga) and clover (*Trifolium pratense*, var. Merula) were transplanted to the soil cores and regularly watered as required. After 6 weeks of plant growth, pots were watered close to field capacity and received 150 ml of a fertilizer solution containing 68.86 mM $KNO_3$ and 5.19 mM $KH_2PO_4$, corresponding to an amount of 60 kg N $ha^{-1}$ and 10 kg P $ha^{-1}$. One day after fertilization, a heavy rainfall of 24mm was simulated by adding 1000ml of water using rainfall simulators and excess water was allowed to drip out the bottom of the soil cores. Directly after the artificial rainfall, $N_2O$ emissions were measured using a TEI 46C automated infrared gas-analyzer (Thermo Fisher Scientific, Waltham, MA, USA). Daily $N_2O$ fluxes were integrated to obtain the total **amount of $N_2O$ emitted** per soil core during the 5 days of measurement.

*Life cycle assessment*

To assess the environmental impact of the investigated cropping systems, a life cycle assessment (LCA) was performed over the 6-year crop rotation. The LCA was conducted by means of SALCA (Nemecek *et al.*, 2010; Nemecek *et al.*, 2011), which includes the use of life cycle inventories from the ecoinvent database (ecoinvent Centre, 2010). SALCA comprises the SALCA database and models for estimating direct field emissions. A detailed description of the method can be found in Prechsl *et al.* (2017). For the purpose of this study, we included the following impact categories: **global warming potential** (100 years; kg CO2 eq.; IPCC, 2007), **Aquatic eutrophication potential** (kg N and P eq.; CML01) and **aquatic ecotoxicity potential** (1,4-dichlorobenzene eq.; CML01). For each impact category we used two functional units, **per product (cereal unit (CU)) and per area (ha)**. These two units are linked to two foci: a) products with low environmental impacts and b) land use with low environmental impacts. CU of a product expresses the nutrition value for pig fattening relative to 100 kg barley, which is defined as the reference with a CU of 1. The borders of a field defined the spatial boundaries of the agricultural cropping system. Upstream emissions and resource use for the provision of infrastructure and the production of commodities (e.g. fertilizers) were also included.

**Ecosystem function calculation**

Along the first 6-year rotation, sampling intensity of the parameters varied. Some were assessed yearly (e.g. yield, weed cover and richness), while others were assessed in specific years, mostly in the 4$^{th}$ year of the rotation (e.g. erosion risk, soil aggregation, N cycle parameters), or modelled based on management and yield information (e.g. LCA parameters). The data comprises two sub-datasets: i) parameters assessed at the plot level where the blocks (n=4 per experiment) are used as replicates, and ii) parameters calculated based on field management information where the crops (n=4, wheat, maize, beans, ley) are used as replicates (costs, working hours, global warming potential per ha and CU, Aquatic eutrophication potential per ha and CU and aquatic ecotoxicity potential per ha and CU). For these two datasets, mean values at the cropping system and replicate level (blocks and crops, respectively) were computed before merging both datasets. Subsequently, data were scaled using the z-transformation function (overall mean of 0 ± SD) to be able to combine different parameters into composite variables.

Some parameters were directly used as proxy for a function, while others were first bundled in composite variables when contributing to same variable category according to the tree structure in Figure 1. Note that for parameters that represent an undesirable aspect from an agronomical (e.g. weed pressure), environmental (e.g. N leaching, global warming potential) or economic (e.g. costs) perspective, the data were multiplied by -1 (inverted around the 0 mean) to maintain directional change with other ecosystem functions, such that an increase in function value always represent a more desirable state. Overall, 14 ecosystem functions were derived out of the 41 parameters assessed. These 14 ecosystem functions were further grouped into the four categories supporting, regulating, provisioning and economic services (Figure 1, Table S4). Finally, the 14 ecosystem functions were scaled between 0 and 1 to ease readability. Similarly to Byrnes *et al.* (2014), we make no assumption of independence between functions, even if functions in an ecosystem are often correlated. The main reasons are that we were interested in single function performance and our EMF analyses should take into account trade-offs and synergies between functions.

**Multifunctionality assessments**

To assess the overall performance of the investigated cropping systems, we calculated different EMF values and used different scenarios, weighting functions and service categories differently. We first calculated EMF with the averaging method, giving equal weight to each of the 14 functions. We then calculated EMF in the same way but at the ecosystem service level, weighting supporting, regulating, provisioning and economic service categories equally. This made it possible to remove bias due to uneven function numbers between service categories. Further, we calculated different EMF scenarios giving more weight to either regulating or provisioning services. We also calculated different diversity measures of function delivery for each cropping systems following the approach of Hölting et al. (2019) including alpha- (diversity of ecosystem function delivery) and beta- (total abundance-based dissimilarities of ecosystem function supply among all cropping systems) multifunctionality. We finally performed a continuous threshold analysis on the alpha diversity measure in order to assess the stability of function delivery over a wide range of thresholds following Byrnes *et al.* (2014).

**Statistical analyses**

Statistical analyses were performed in R version 3.6.3 (R Core Team, 2020) and the packages emmeans (Lenth *et al.*, 2018), vegan (Oksanen *et al.*, 2013), betapart (Baselga and Orme, 2012) and multifunc (Byrnes, 2017). All assessed parameters were subjected to variance analyses in an ANOVA. The term block nested in experiment was considered as random effects and cropping system as fixed effect. The factor cover crop (sub-plot level in the experiment) was not considered in this study and mean values per main-plots were used for the analyses. Similarly, the mean over all crops was used, for parameters that were assessed yearly, as intrinsic differences between crops is not the focus of this study. The effects of cropping system on the 14 calculated ecosystem functions, the four service categories as well as the various multifunctionality indexes were analyzed in an ANOVA with cropping system as fixed factor. Pairwise comparisons were tested on estimated marginal means among the four cropping systems for all variables (absolute parameters and scaled variables).

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## Supplementary information

**Table S1. Cropping system description of the Farming System and Tillage experiment.** C-IT: conventional intensive tillage, C-NT: conventional no tillage, O-IT: organic intensive tillage, O-RT: organic reduced tillage. N: nitrogen, P: phosphorus, K: potassium, LU: livestock unit23

| | systems | | | |
|---|---|---|---|---|
| | **C-IT** | **C-NT** | **O-IT** | **O-RT** |
| **Tillage** | moulboard plough (20cm)<br>rotary harrow | -<br>- | moulboard plough (20cm)<br>rotary harrow | disk harrow, rotary harrow (<10cm) |
| **Fertilization** | mineral fertilizer (N, P, K) | mineral fertilizer (N, P, K) | cattle slurry ~ 1.4 LU/ha | cattle slurry ~ 1.4 LU/ha |
| **Weed control** | post-emergence herbicides | Glyphosate<br>post-emergence herbicides | harrowing (wheat)<br>hoeing (maize, bean) | harrowing (wheat)<br>hoeing (maize, bean) |
| **Pest/disease control** | seed coating (wheat, maize)<br>Trichogramma (maize)<br>Insecticide (bean) | seed coating (wheat, maize)<br>Trichogramma (maize)<br>Insecticide (bean) | -<br>Trichogramma (maize)<br>- | -<br>Trichogramma (maize)<br>- |

## Table S2. Field operations summary

| | Wheat cv. 'Titlis' | | | Maize cv. 'Padrino' | | | Field bean cv. 'Fuego' | | |
|---|---|---|---|---|---|---|---|---|---|
| | operation | FAST I | FAST II | operation | FAST I | FAST II | operation | FAST I | FAST II |
| **Cover crop** | sowing | 24.08.2009 | 10.08.2010 | sowing | 11.08.2010 | 11.08.2011 | | | |
| destruction C-IT, O-IT, O-RT | mulching | 08.10.2009 | 08.10.2010 | mulching | 15.04.2011 | 27.04.2012 | | | |
| growth period (days) | | 44 | 58 | | 244 | 256 | | | |
| **Tillage** | | | | | | | | | |
| Intensive tillage (C-IT, O-IT) | plough (20cm) | 08.10.2009 | 09.10.2010 | plough (20cm) | 18.04.2011 | 28.04.2012 | plough (20cm) | 12.03.2012 | 05.04.2013 |
| | rotary harrow (5cm) | 20.10.2009 | 11.10.2010 | rotary harrow (5cm) | 28.04.2011 | 04.05.2012 | rotary harrow (5cm) | 13.03.2012 | 16.04.2013 |
| ORG reduced tillage (O-RT) | disk harrow (5cm) | 20.10.2009 | 12.10.2010 | rotary harrow (5cm) | 29.04.2011 | 04.05.2012 | rotary harrow (5cm) | 13.03.2012 | 16.04.2013 |
| CONV no tillage (C-NT) | Glyphosate (4 l/ha) | 09.10.2009 | 08.10.2010 | Glyphosate (4 l/ha) | 08.04.2011 | 17.04.2012 | | | |
| **Sowing** | 400 seed/$m^2$ | 21.10.2009 | 13.10.2010 | 9.5 plant/$m^2$ | 29.04.2011 | 04.05.2012 | 45 plant/$m^2$ | 14.03.2012 | 16.04.2013 |
| row distance | 16.6 cm | | | 70 cm | | | 50 cm | | |
| coating C-IT, C-NT | | | | | | | | | |
| **Fertilization** | | | | | | | | | |
| CONV | | | | | | | | | |
| Total P/K | | | | 47 / - kg/ha | 10.05.2011 | 08.05.2012 | 125 / 194 kg/ha | | |
| N application 1 | 50 kgN/ha | 19.03.2010 | 16.03.2011 | 30 kgN/ha | 10.05.2011 | 08.05.2012 | | | |
| N application 2 | 30 kgN/ha | 09.04.2010 | 05.04.2011 | 60 kgN/ha | 16.07.2011 | 15.06.2012 | | | |
| N application 3 | 30 kgN/ha | 17.05.2010 | 09.05.2011 | | | | | | |
| N application 4 | | | | | | | | | |
| ORG | | | | | | | | | |
| slurry application 1 | 30 $m^3$/ha | 19.03.2010 | 16.03.2011 | 30 $m^3$/ha | 12.05.2011 | 02.05.2012 | | | |
| slurry application 2 | 30 $m^3$/ha | 09.04.2010 | 05.04.2011 | 40 $m^3$/ha | 16.07.2011 | 24.05.2012 | | | |
| slurry application 3 | | | | | | | | | |
| slurry application 4 | | | | | | | | | |
| **Weed control** | | | | | | | | | |
| CONV | herbizide | 25.03.2010 | 16.03.2011 | herbizide | 31.05.2011 | 31.05.2012 | herbizide | 15.03.2012 | 18.04.2013 |
| ORG | harrow | 27.04.2010 | 16.03.2011 | hoing | 06.06.2011 | 31.05.2012 | hoing | 28.04.2012 | 15.05.2013 |
| | | | | hoing | 24.06.2011 | 20.06.2012 | hoing | 15.05.2012 | 08.06.2013 |
| **Harvest** | | 04.08.2010 | 26.07.2011 | | 06.10.2011 | 17.10.2012 | | 13.08.2012 | 23.08.2013 |

| | Wheat cv. 'Titlis' | | | Grass-clover 1st year UFA330 | | | Grass-clover 2nd year | | |
|---|---|---|---|---|---|---|---|---|---|
| | operation | FAST I | FAST II | operation | FAST I | FAST II | operation | FAST I | FAST II |
| **Cover crop** | | | | mulcher | 29.08.2013 | | | | |
| destruction C-IT, O-IT, O-RT | | | | | | | | | |
| growth period (days) | | | | | | | | | |
| **Tillage** | | | | | | | | | |
| Intensive tillage (C-IT, O-IT) | plough (20cm) | 19.10.2012 | 18.10.2013 | mulcher | 29.08.2013 | | | | |
| | rotary harrow (5cm) | 22.10.2012 | 22.10.2013 | Rotary tiller (5cm) | 30.08.2013 | 25.08.2014 | | | |
| ORG reduced tillage (O-RT) | rotary harrow (5cm) | 22.10.2012 | 22.10.2013 | Rotary tiller (5cm) | 30.08.2013 | 25.08.2014 | | | |
| CONV no tillage (C-NT) | Glyphosate (3.5 l/ha) | 02.10.2012 | 25.09.2013 | - | - | - | | | |
| **Sowing** | 400 seed/$m^2$ | 24.10.2012 | 22.10.2013 | 33 kg/ha | 30.08.2013 | 25.08.2014 | | | |
| row distance | 16.6 cm | | | 16.6 cm | | | | | |
| coating C-IT, C-NT | | | | Roller | 30.08.2013 | - | | | |
| **Fertilization** | | | | | | | | | |
| CONV | | | | | | | | | |
| Total P/K | 60 / 100 kg/ha | 22.10.2013 | 17.10.2013 | 90 / 275 kg/ha | 13.03.2014 | 11.03.2015 | 80 / 240 kg/ha | 11.03.2015 | 22.03.2016 |
| N application 1 | 60 kgN/ha | 22.03.2013 | 17.03.2014 | 40 kgN/ha | 17.03.2014 | 19.03.2015 | 40 kgN/ha | 19.03.2015 | 15.03.2016 |
| N application 2 | 30 kgN/ha | 23.04.2013 | 15.04.2014 | 30 kgN/ha | 05.05.2014 | 13.05.2015 | 30 kgN/ha | 13.05.2015 | 26.05.2016 |
| N application 3 | 30 kgN/ha | 15.05.2013 | 26.05.2014 | 30 kgN/ha | 17.06.2014 | 07.07.2015 | 30 kgN/ha | 07.07.2015 | 01.07.2016 |
| N application 4 | | | | 30 kgN/ha | 29.07.2014 | 13.08.2015 | | | |
| ORG | | | | | | | | | |
| slurry application 1 | 30 $m^3$/ha | 02.04.2013 | 20.03.2014 | 30 $m^3$/ha | 20.03.2014 | 19.03.2015 | 30 $m^3$/ha | 19.03.2015 | 22.03.2016 |
| slurry application 2 | 30 $m^3$/ha | 22.04.2013 | 09.04.2014 | 30 $m^3$/ha | 05.05.2014 | 19.05.2015 | 30 $m^3$/ha | 19.05.2015 | 26.05.2016 |
| slurry application 3 | | | | 30 $m^3$/ha | 17.06.2014 | 07.07.2015 | 30 $m^3$/ha | 07.07.2015 | 04.07.2016 |
| slurry application 4 | | | | 30 $m^3$/ha | 29.07.2014 | 13.08.2015 | 30 $m^3$/ha | 13.08.2015 | |
| **Weed control** | | | | | | | | | |
| CONV | herbizide | 16.04.2013 | 18.03.2014 | | | | | | |
| ORG | harrow | 07.09.2012 | 19.03.2014 | | | | | | |
| | harrow | 17.04.2013 | | | | | | | |
| **Harvest** | | 06.08.2013 | 28.07.2014 | 1st cut | 23.04.2014 | 07.05.2015 | 1st cut | 07.05.2015 | 10.05.2016 |
| | | | | 2nd cut | 11.06.2014 | 24.06.2015 | 2nd cut | 24.06.2015 | 29.06.2016 |
| | | | | 3rd cut | 24.07.2014 | 05.08.2015 | 3rd cut | 05.08.2015 | 11.08.2016 |
| | | | | 4th cut | 11.09.2014 | 15.09.2015 | 4th cut | 15.09.2015 | 20.09.2016 |
| | | | | 5th cut | 07.11.2014 | | | | |

**Table S3. Fertilization summary for the organic and conventional systems of the FAST experiment** [kg ha$^{-1}$].

| | Wheat | Maize | Field bean | Wheat | Grass/Clover 1 | Grass/Clover 2 | total input | yearly input |
|---|---|---|---|---|---|---|---|---|
| | **ORGANIC (cattle slurry)** | | | | | | | |
| m3 slurry/ha | 60 (30+30) | 70 (30+40) | | 60 (30+30) | 120 (4*30) | 105 (4*30 I,3*30 II) | | |
| TS | 3216 | 3670 | | 3312 | 6434 | 5555 | 22187 | 3698 |
| OS | 2262 | 2643 | | 2271 | 4364 | 3650 | 15190 | 2532 |
| $N_{tot}$ | 119 | 132 | | 95 | 212 | 168 | **726** | **121** |
| N-$NH_4$ | 45 | 67 | | 45 | 79 | 68 | 305 | 51 |
| $P_2O_5$ | 29 | 43 | | 37 | 98 | 70 | **277** | **46** |
| $K_2O$ | 175 | 221 | | 236 | 495 | 410 | **1537** | **256** |
| Mg | 23 | 31 | | 24 | 60 | 36 | **174** | **29** |
| | **CONVENTIONAL (mineral)** | | | | | | | |
| N | 110 | 90 | 0 | 120 | 130 | 100 | **550** | **92** |
| $P_2O_5$ | 0 | 82 | 63 | 88 | 90 | 80 | **402** | **67** |
| $K_2O$ | 0 | 69 | 97 | 128 | 275 | 240 | **809** | **135** |
| Mg | 22 | 12 | 0 | 24 | 26 | 20 | **104** | **17** |

**Table S4: Assessed parameters, ecosystem functions and services used for multifunctionality calculations.**

| services | function | parameter | unit | method | references |
|---|---|---|---|---|---|
| supporting | **Plant diversity (PlantDIV)** | Weed diversity | # species | Visual assessment, field | Method section |
| | **Soil biodiversity (SoilDIV)** | Soil bacterial richness | # OTU | Illumina sequencing | (Hartman et al., 2018) |
| | | Soil fungi richness | # OTU | Illumina sequencing | |
| | | AMF spore richness | # species | microscopy | (Säle et al., 2015) |
| | **Soil fertility (SoilFERT)** | Soil Corg | % | dichromate extraction | (Eidgenössische Forschungsanstalten, 1996) |
| | | Soil Ntot | % | elemental analysis | |
| | | Soil Pavailable | mg P/kg | CO2 extraction | |
| | | Soil K available | mg K/kg | CO2 extraction | |
| | **Soil Biota (SoilBIO)** | Microbial biomass C | mg C/kg | fumigation | |
| | | Bacterial PLFA | i15:0, i16:0, i17:0, a15:0, a17:0, cy17:0, cy19:0,10Me16b, 10Me17:0 and 10Me18:0 | Fatty acid signature | (Hydbom et al., 2017) |
| | | Fungi PLFA | 18:1w9, 18:2w6 | Fatty acid signature | |
| | | AMF NLFA | N161w5 | Fatty acid signature | |
| | | AMF PLFA | 16:1w5 | Fatty acid signature | |
| | | AMF spore density | Spores/g | microscopy | (Säle et al., 2015) |
| | | Earthworm biomass | $g/m^2$ | Collection from soil samples field | Method section |
| | | Earthworm density | $\#/m^2$ | Collection from soil samples field | |
| | **Soil structure (SoilPHY)** | Aggregate Mean Weight Diameter | micrometer | wet sieving | (Puerta et al., 2018) |
| | | Corg/clay ratio | - | calculation | (Johannes et al. 2017) |
| regulating | **Soil protection (SoilPRO)** | sediment discharge | kg/ha h | In situ, rain simulation | (Seitz et al., 2018) |
| | **Water protection (WaterPRO)** | Aquatic eutrophication potential N | kg N eq./ha and /CU | Life Cycle Assessment | (Prechsl et al., 2017) |
| | | Aquatic eutrophication potential P | kg P eq./ha and /CU | Life Cycle Assessment | |
| | | Aquatic ecotoxicity potential | 1,4-dichlorobenzene eq./ha and /CU | Life Cycle Assessment | |
| | | N leaching potential | kg N | intact soil cores | Method section |
| | **Climate protection (ClimPRO)** | Global warming potential (100 years) | kg CO2 eq./ha and /CU | Life Cycle Assessment | (Prechsl et al., 2017) |
| | | N2O emission potential | mg N | intact soil cores | Method section |
| provisioning | **Food production (Prod)** | Marketable yield (grain, forage) | t/ha DM | field | Method section |
| | | N concentration yield | g N / kg DM | elemental analysis | Method section |
| | **Weed control** | Weed cover in main crops | % soil cover | Visual assessment, field | Method section |
| | | Weed seed bank | $\# seeds/m^2$ | greenhouse | Method section |
| | **Fertilizer Utilization Efficiency (Fertuse)** | N content yield / N applied | kg harvested / kg applied | calculation | - |
| | | P content yield / P applied | kg harvested / kg applied | calculation | - |
| | | K content yield / K applied | kg harvested / kg applied | calculation | - |
| economic | **Income** | Product revenue | CHF.- | Full cost analysis | Method section |
| | | Costs | CHF.- | Full cost analysis | Method section |
| | | Remuneration | CHF.- / hours | Full cost analysis | Method section |
| | **Work efficiency (WorkEff)** | Working hours | hours / ha | Full cost analysis | Method section |
| | **Autonomy** | Subsidies proportion (Subsidies/Total income) | CHF.- | Full cost analysis | Method section |

**Table S5. Absolute values for the 41 included parameters averaged over the 6-year crop rotation** (mean ± standard errors, n=4).

| Service category | parameter | unit | C-IT | C-NT | O-IT | O-RT |
|---|---|---|---|---|---|---|
| supporting | weed richness | # species | 2.0 ± 0.3 | 1.8 ± 0.2 | 6.6 ± 0.2 | 6.0 ± 0.2 |
| | soil Corg | % | 1.39 ± 0.04 | 1.39 ± 0.08 | 1.38 ± 0.06 | 1.44 ± 0.02 |
| | soil Ntot | % | 0.17 ± 0.003 | 0.17 ± 0.006 | 0.17 ± 0.008 | 0.18 ± 0.003 |
| | soil Pavail | mg P/kg | 1.175 ± 0.074 | 1.328 ± 0.131 | 0.856 ± 0.04 | 0.986 ± 0.1 |
| | soil.Kavail | mg K/kg | 28.8 ± 2.4 | 37.5 ± 4.3 | 26.5 ± 2.2 | 32.4 ± 2.6 |
| | SOC / Clay ratio | - | 0.065 ± 0.001 | 0.069 ± 0.003 | 0.067 ± 0.002 | 0.066 ± 0 |
| | aggregate (MWD) | micrometer | 923 ± 26 | 1075 ± 41 | 991 ± 38 | 1136 ± 33 |
| | microbial biomass C | mg C/kg | 502 ± 23 | 516 ± 55 | 512 ± 35 | 566 ± 22 |
| | bacteria PLFA | mol% | 96.5 ± 4.8 | 103.2 ± 6.1 | 103.3 ± 3.2 | 106.8 ± 5.5 |
| | fungi PLFA | mol% | 14.2 ± 0.4 | 14.8 ± 1.3 | 14.6 ± 1.2 | 16.6 ± 0.7 |
| | AMF NLFA | mol% | 11.6 ± 0.6 | 12.8 ± 1.5 | 13.2 ± 1.0 | 15.5 ± 1.4 |
| | AMF PLFA | mol% | 8.8 ± 0.2 | 9.6 ± 0.9 | 9.4 ± 0.8 | 10.6 ± 0.4 |
| | AMF spore density | Spores/g | 22.7 ± 1.1 | 18.8 ± 1.2 | 21.2 ± 1.3 | 23.0 ± 1.0 |
| | earthworms density | g/m2 | 359 ± 40.1 | 737 ± 23.2 | 656 ± 81.4 | 603 ± 79.5 |
| | earthworms weight | #/m2 | 61 ± 7.8 | 152 ± 7.5 | 112 ± 16.0 | 120 ± 16.2 |
| | bacterial richness | # OTU | 1193 ± 21 | 1119 ± 39 | 1216 ± 26 | 1144 ± 45 |
| | fungi richness | # OTU | 550 ± 18 | 557 ± 10 | 590 ± 16 | 563 ± 12 |
| | AMF spore richness | # species | 19.1 ± 0.3 | 24.0 ± 1.2 | 21.5 ± 0.5 | 25.6 ± 1.2 |
| regulating | sediment discharge | kg soil/ha h | 346 ± 82 | 24 ± 4 | 187 ± 31 | 73 ± 24 |
| | Eutr_aq_N_ha | kg N eq./ha | 38 ± 8 | 34 ± 8 | 37 ± 7 | 38 ± 8 |
| | Eutr_aq_N_CU | kg N eq./CU | 0.006 ± 0.001 | 0.005 ± 0.001 | 0.008 ± 0.002 | 0.014 ± 0.008 |
| | N leaching pot. | kg N | 24.3 ± 5.6 | 11.9 ± 3.9 | 19.8 ± 5.1 | 13.1 ± 1.7 |
| | Eutr_aq_P_ha | kg P eq./ha | 2.22 ± 0.30 | 1.80 ± 0.30 | 1.13 ± 0.14 | 0.71 ± 0.08 |
| | Eutr_aq_P_CU | kg P eq./CU | 0.00 ± 0.00 | 0.00 ± 0.00 | 0.00 ± 0.00 | 0.00 ± 0.00 |
| | Ecotox_aq_pest_ha | 1,4-dichlorobenzene eq./ha | 708 ± 228 | 649 ± 225 | 138 ± 38 | 109 ± 26 |
| | Ecotox_aq_pest_CU | 1,4-dichlorobenzene eq./CU | 0.114 ± 0.043 | 0.110 ± 0.041 | 0.030 ± 0.009 | 0.037 ± 0.013 |
| | GWP_ha | kg CO2 eq./ha | 2457 ± 327 | 2194 ± 359 | 1324 ± 312 | 1175 ± 294 |
| | GWP_CU | kg CO2 eq./CU | 0.39 ± 0.08 | 0.36 ± 0.06 | 0.30 ± 0.09 | 0.43 ± 0.17 |
| | $N_2O$ emmission pot. | mg N | 19.0 ± 1.5 | 18.8 ± 1.3 | 17.6 ± 0.5 | 17.3 ± 2.0 |
| provisioning | marketable yield | t/ha DM | 7.1 ± 0.15 | 6.7 ± 0.10 | 5.6 ± 0.07 | 4.7 ± 0.27 |
| | N concentration yield | g N / kg DM | 26.7 ± 0.26 | 26.5 ± 0.11 | 24.8 ± 0.21 | 24.8 ± 0.24 |
| | N fertilizer use eff. | kg harvested / kg applied | 0.97 ± 0.02 | 0.95 ± 0.009 | 0.65 ± 0.02 | 0.57 ± 0.03 |
| | P fertilizer use eff. | kg harvested / kg applied | 0.42 ± 0.01 | 0.40 ± 0.01 | 0.51 ± 0.01 | 0.46 ± 0.02 |
| | K fertilizer use eff. | kg harvested / kg applied | 0.87 ± 0.02 | 0.84 ± 0.01 | 0.38 ± 0.01 | 0.37 ± 0.02 |
| | weed cover | % soil cover | 3.0 ± 0.8 | 5.7 ± 0.3 | 21.6 ± 1.4 | 31.0 ± 0.8 |
| | weed seedbank | # seeds/m2 | 8878 ± 840 | 16179 ± 4278 | 40661 ± 4902 | 27916 ± 1513 |
| economic | product revenue | CHF.- | 2934.57 ± 64.64 | 2763.28 ± 35.93 | 4070.76 ± 29.11 | 3163.58 ± 209.06 |
| | costs | CHF.- | 4875.07 ± 912.96 | 4432.22 ± 996.65 | 4856.80 ± 891.80 | 4604.61 ± 970.37 |
| | remuneration | CHF.- / hours | 44.13 ± 2.65 | 57.29 ± 1.77 | 109.81 ± 1.51 | 102.74 ± 7.21 |
| | subsidies | CHF.- | 1466.67 ± 0.00 | 1633.33 ± 0.00 | 2400.00 ± 0.00 | 2766.67 ± 0.00 |
| | Total_income | CHF.- | 4401.24 ± 64.64 | 4396.61 ± 35.93 | 6470.76 ± 29.11 | 5930.25 ± 209.06 |
| | Working_hours | hours / ha | 33.3 ± 1.50 | 30.5 ± 1.09 | 34.4 ± 1.58 | 33.1 ± 1.55 |
| | subsidies proportion | % | 0.3 ± 0.01 | 0.4 ± 0.00 | 0.4 ± 0.00 | 0.5 ± 0.02 |

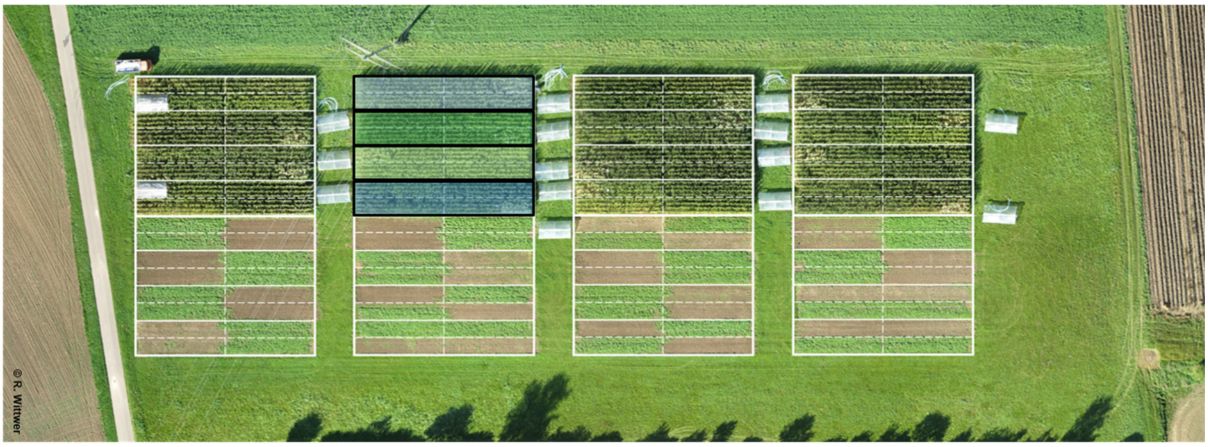


**Figure S1. Aerial picture of the FAST experiment** (2017).

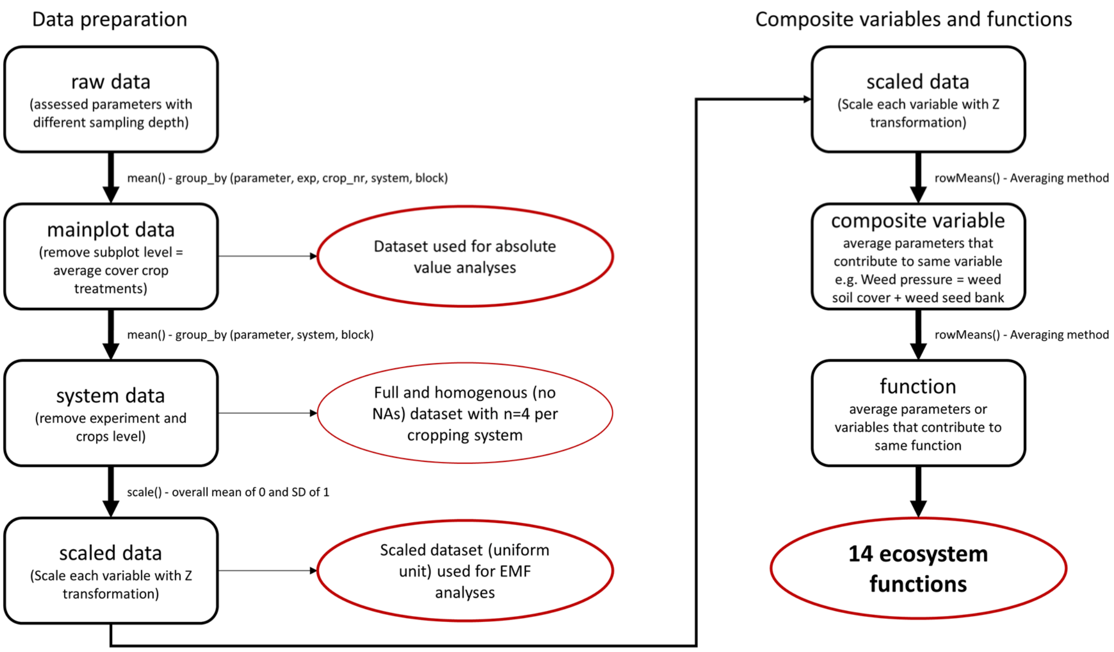


**Figure S2: Data transformation workflow for the ecosystem multifunctionality (EMF) analyses.**

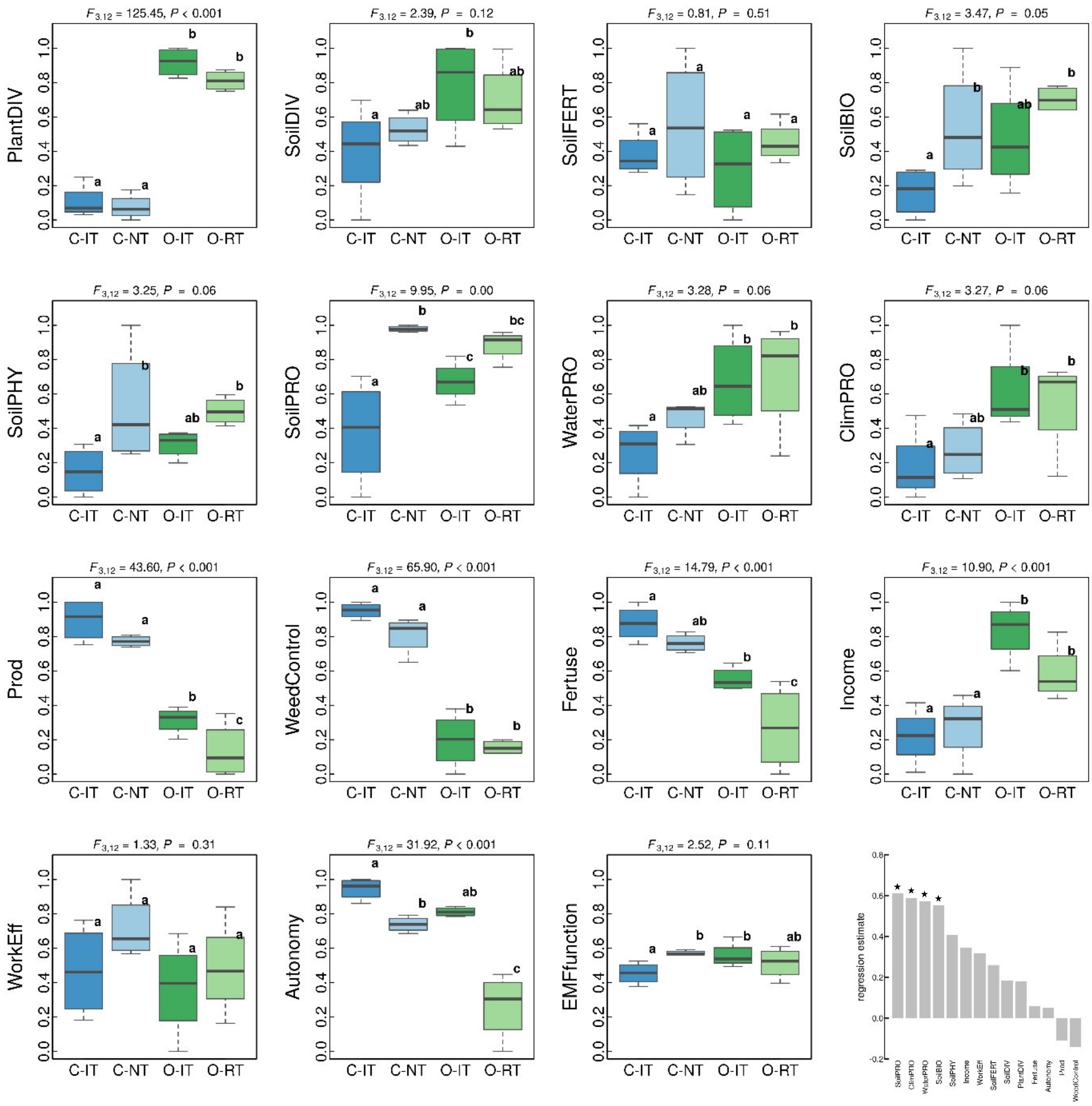

**Figure S3. Boxplots with scaled values for the 14 computed ecosystem functions used for multifunctionality assessments** (Z score scaled between 0 and 1**).** F-values and p-values are displayed above each plot and different letters indicate significant differences between the four cropping systems (pairwise comparison with estimated marginal means (emmeans package), n = 4). Bottom right panel display regression estimate for each functions with overall multifunctionality (* indicate significant estimate).

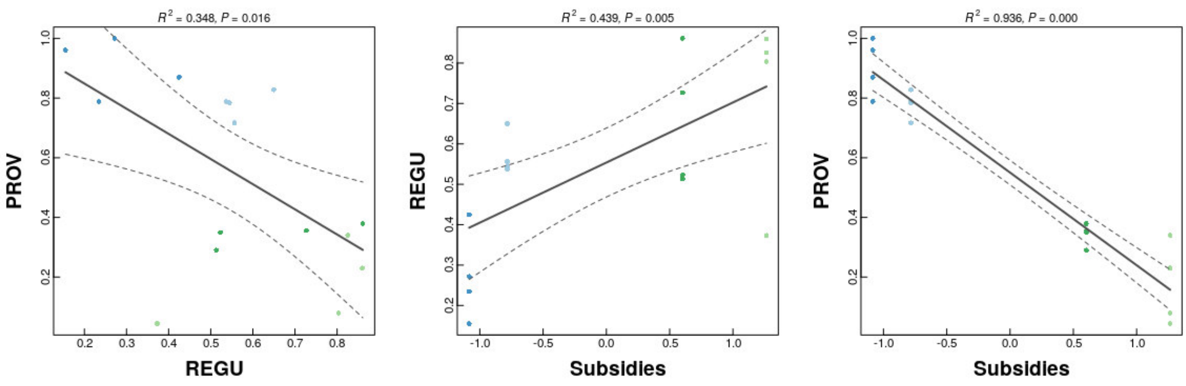


**Figure S4. Relationship between subsidies, regulating and provisioning service delivery.**

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# CHAPTER 2

## Cover crops support ecological intensification of arable cropping systems

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**Abstract**

A major challenge for agriculture is to enhance productivity with minimum impact on the environment. Several studies indicate that cover crops could replace anthropogenic inputs and enhance crop productivity. However, so far, it is unclear if cover crop effects vary between different cropping systems, and direct comparisons among major arable production systems are rare. Here we compared the short-term effects of various cover crops on crop yield, nitrogen uptake, and weed infestation in four arable production systems (conventional cropping with intensive tillage and no-tillage; organic cropping with intensive tillage and reduced tillage). We hypothesized that cover cropping effects increase with decreasing management intensity. Our study demonstrated that cover crop effects on crop yield were highest in the organic system with reduced tillage (+24%), intermediate in the organic system with tillage (+13%) and in the conventional system with no tillage (+8%) and lowest in the conventional system with tillage (+2%). Our results indicate that cover crops are essential to maintaining a certain yield level when soil tillage intensity is reduced, or when production is converted to organic agriculture. Thus, the inclusion of cover crops provides additional opportunities to increase the yield of lower intensity production systems and contribute to ecological intensification.

## Introduction

Agriculture is facing one of the biggest challenges of our time, namely to produce enough high quality food while reducing external inputs and minimizing negative environmental impacts. Intensive conventional agriculture can contribute to high crop productivity. However, with its excessive use of pesticides and mineral fertilizers, intensive agriculture has a negative impact on the environment by decreasing biodiversity, causing pollution and eutrophication of water, and degrading soil quality (Stoate *et al.*, 2001; Geiger *et al.*, 2010; Bender *et al.*, 2016).

To mitigate this trend, ecological intensification has been proposed (Cassman, 1999; Dore *et al.*, 2011; Bommarco *et al.*, 2013; Tittonell, 2014). Ecological intensification is defined as the environmentally friendly replacement of anthropogenic inputs and/or enhancement of crop productivity by including agricultural practices that promote regulating and supporting ecosystem services (Bommarco *et al.*, 2013). In Europe, efforts are particularly dedicated to reduce the environmental impact of intensive agriculture and the use of synthetic, anthropogenic inputs. Various strategies and management practices have been suggested that could be used for ecological intensification in arable systems. These include organic farming (Mäder *et al.*, 2002; Reganold and Wachter, 2016), agricultural practices with reduced or no soil tillage (e.g. conservation agriculture) (Hobbs *et al.*, 2008), and the use of cover crops instead of longer bare fallow periods (Sainju and Singh, 1997; Doltra and Olesen, 2013).

Organic farming is proposed for ecological intensification because it promotes biodiversity and soil fertility and has a reduced environmental impact (Mäder *et al.*, 2002; Birkhofer *et al.*, 2008; Crowder *et al.*, 2010; Verbruggen *et al.*, 2010; Gattinger *et al.*, 2012; Tuomisto *et al.*, 2012). Conservation agriculture (CA), in turn, contributes to soil protection, sustains soil quality, and results in a better use of natural resources (Hobbs *et al.*, 2008). Despite these clear ecological benefits, organic yields (de Ponti *et al.*, 2012; Seufert *et al.*, 2012) and yields under conservation agriculture (Pittelkow *et al.*, 2015a) are often below yields in conventional systems. This yield gap can reduce the positive environmental footprint of organic farming and CA compared to conventional farming because more land is needed to produce the same amount of food. Moreover, although organic and no-tillage agriculture have received increased attention in Europe, and are sometimes actively supported by governmental direct payments (e.g. in Switzerland by FOAG), less than 10% of arable land is actually under no-till or organic agriculture.

Over the last decade, substantial effort has been devoted to implementing CA practices (minimal tillage, permanent soil cover and diverse crop rotation) under organic production because a combination of both strategies could have synergistic effects and further improve soil quality (Peigne *et al.*, 2007; Teasdale *et al.*, 2007; Mäder and Berner, 2012). A recent meta-analysis by Cooper *et al.* (2016) concluded that organic yields are not necessarily lower under reduced tillage but that soil carbon storage is improved. However, the application of reduced or no tillage practices often increases problems related to weed control and crop nutrition (Gruber and Claupein, 2009; Carr *et al.*, 2012; Mirsky *et al.*, 2012; Armengot *et al.*, 2015). One way to tackle these issues is the inclusion of cover crops in the crop rotation.

Cover crops are implemented between two main crops and are known to provide various ecological services in agro-ecosystems, such as protection against soil erosion, reduction of nutrient losses, improvement of soil and water quality, and to some extent, the reduction of weeds and pests (Dabney *et al.*, 2001; Hartwig and Ammon, 2002; Dorn *et al.*, 2015). Furthermore, adding nitrogen (N) fixing legume species as a cover crop can improve N nutrition of the succeeding main crop and increase the soil N organic pool (Thorup-Kristensen *et al.*, 2003). Thus, cover crops can contribute to a more sustainable agriculture and alleviate weed and crop nutrition issues related to organic and conservation agriculture. Despite these advantages, cover crops are generally not widely used by farmers, mainly due to additional costs and labour requirements. Moreover, cover crop effects on productivity, crop nutrition, or weed control are variable and depend on cover crop species, soil type, and climate (Thorup-Kristensen *et al.*, 2003). To date, most research on cover crops has focused on their effects on water quality and N dynamics (Dabney *et al.*, 2001; Thorup-Kristensen *et al.*, 2003) or on the choice of plant species (Dorn *et al.*, 2015) and management options (Thorup-Kristensen and Dresboll, 2010; Alonso-Ayuso *et al.*, 2014) (e.g. sowing and killing techniques and dates). The impact of legume cover crops on productivity is known to be strongly related to the amount of nitrogen fertilization (Miguez and Bollero, 2005; Gabriel and Quemada, 2011; Liebman *et al.*, 2012), and the type of cover crop and tillage system influence nutrient mineralisation dynamics as well as weed control potential. Nevertheless, so far, few replicated randomized field experiments have tested cover crop effects in different arable systems simultaneously, and little is known about the relative importance of cover crops in different cropping systems.

To address this question, we set up a long-term arable cropping system experiment, known as the Swiss farming systems and tillage experiment (FAST). In this experiment, we compare the effects of four cover crop treatments (a legume cover crop, a non-legume cover crop, a mixture of several species, and a control treatment without cover crops (bare fallow)), simultaneously in four different arable production systems: conventional and organic arable cropping systems, each with intensive tillage (plough) or with soil conservation tillage treatments (no-tillage and reduced tillage for conventional and organic systems, respectively). These four production systems reflect a management intensity gradient where conventional intensive tillage has the highest intensity and organic reduced tillage has the lowest intensity in terms of external anthropogenic inputs and soil disturbance per unit area (Table 1). In the present study, we assessed the short-term effects of cover crops on wheat and maize yield, crop nutrition, and weed infestation. We hypothesized that:

I. The effects of cover crops increase with reduced management intensity as the services provided by cover crops compensate for diminishing intensity.

II. Effects of cover crops are highest in the organic reduced tillage system where all three input factors (pesticides, mineral fertiliser and energy use) are absent or have reduced intensity.

III. Different cover crops differ from each other in their impact on crop yield, and nitrogen-fixing cover crops (e.g. legumes) enhance nitrogen availability.

IV. The implementation of cover crops as an ecological management tool enhances productivity across all production systems.

**Table 1 I Summary of management practices and management intensity of the four production systems in FAST** (C-IT: Conventional intensive tillage, C-NT: Conventional no tillage, O-IT: Organic intensive tillage, O-RT Organic reduced tillage). Management intensity is estimated for each production system using three anthropogenic input factors (Energy use, weed control, and fertilisation). These factors were also used in different studies evaluating agricultural land use intensity(Herzog *et al.*, 2006; Ruiz-Martinez *et al.*, 2015). A detailed calculation is included in Supplementary Table S2 online.

| **Management practices** | **C-IT** | | **C-NT** | | **O-IT** | | **O-RT** | |
|---|---|---|---|---|---|---|---|---|
| Tillage | Plough (20cm), Rotary harrow (5cm) | | - | | Plough (20cm), Rotary harrow (5cm) | | Disk harrow, Rotary harrow (<10cm) | |
| Weed control | Post-emergence herbicides | | Glyphosate, Post-emergence herbicides | | Mechanical (Harrow, hoe) | | | |
| Fertilization | Mineral ($NH_4$-N / $NO_3$-N) | | | | Organic (cattle slurry) | | | |
| **Management intensity** | **C-IT** | | **C-NT** | | **O-IT** | | **O-RT** | |
| **Cover cropping** | **C** | **CC** | **C** | **CC** | **C** | **CC** | **C** | **CC** |
| Energy use (liter fuel $ha^{-1}$ $year^{-1}$) * | 54 | 61 | 18 | 22 | 47 | 55 | 25 | 32 |
| relative scaling § | **0.9** | **1.0** | **0.3** | **0.4** | **0.8** | **0.9** | **0.4** | **0.5** |
| N supply (kg N $ha^{-1}$ $year^{-1}$) ** | 100 | 100 | 100 | 100 | 69 | 69 | 69 | 69 |
| relative scaling § | **1.0** | **1.0** | **1.0** | **1.0** | **0.7** | **0.7** | **0.7** | **0.7** |
| Pesticide (kg $ha^{-1}$ active substance) *** | 2.7 | 2.7 | 5.6 | 5.6 | 0 | 0 | 0 | 0 |
| relative scaling § | **0.5** | **0.5** | **1.0** | **1.0** | **0.0** | **0.0** | **0.0** | **0.0** |
| **Averaged intensity score** | **2.4** | **2.5** | **2.3** | **2.4** | **1.5** | **1.6** | **1.1** | **1.2** |

* Energy use measured as l fuel per ha and year (Nemecek and Kägi, 2007). Includes primary tillage, seedbed preparation, sowing, fertilization, spraying, and mechanical weed control. Sowing (all systems) and mulching (except C-NT) were included as additional management operations for the cover crop treatments.

** Supply of plant available N in the organic systems is calculated as: a * $NH_4$-$N_{slurry}$ + b * ($Ntot_{slurry}$ - $NH_4$-$N_{slurry}$). a: $NH_4$-N volatilization coefficient during application (0.8), b: percent of organic N mineralized (0.35) (Cavigelli *et al.*, 2008). It is assumed that all mineral-N supplied to the conventional system is available to plants.

*** Pesticide measured as kg applied active substances per ha.

§ Relative scaling of the input factors among the production systems was calculated relative to the highest value (=1), for the corresponding impact factor.

## Results

### *Effect of production system and cover crops on grain yield*

Grain yield of wheat and maize varied significantly between the different production systems (Table 2 and Figure 1). The average yield of maize and wheat was highest in the conventional intensive tillage system (C-IT), intermediate in the no tillage conventional system (C-NT) (-8%) and organic intensive tillage system (O-IT) (-31%), and lowest in the organic system with reduced tillage (O-RT) (-46%). Both crops largely responded the same way to the different production systems, with lowest yields in the organic reduced tillage system and highest yields in the conventional systems. Intensive tillage generally increased yield, both for organic (+23%) and conventional production systems (+8%), especially for maize.

Grain yield in the different production systems also varied depending on the cover crop treatment (Table 2 and Figure 1). Averaged across all production systems, the use of legume cover crops and cover crop mixtures significantly increased overall yield of wheat and maize by 12% and 11% respectively, compared to the bare fallow treatment. In contrast, no significant effect of the non-legume cover crop (+3% yield increase) could be observed.

Significant cover crop effects in wheat were only observed within the O-RT system, where wheat yield was significantly higher after the non-legume (white mustard) and legume (common vetch) cover crop treatments (Figure 1 and 2). The general effect of the legume cover crop on wheat was low but still significantly higher compared to the control treatment across all four production systems (+ 9%).

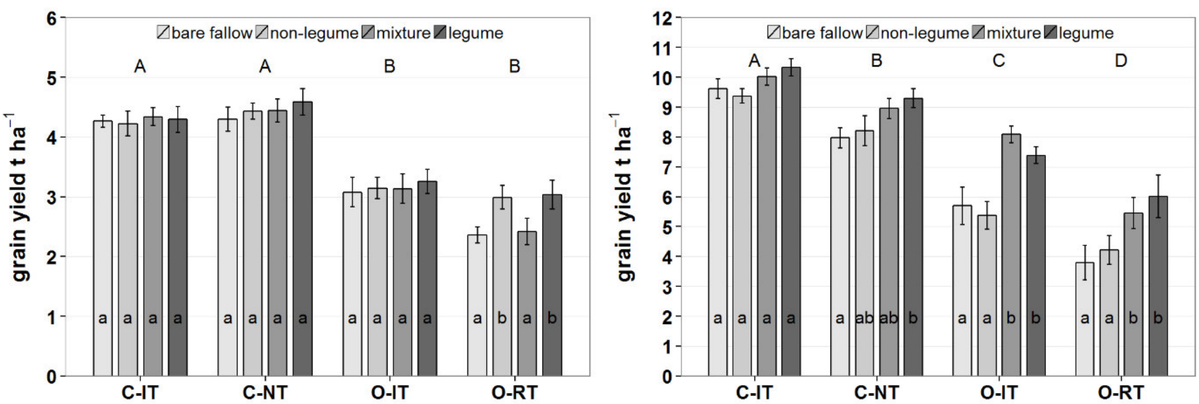


**Figure 1 I Grain yield affected by production systems and cover crops,** winter wheat (left) and maize (right), (mean ± standard errors, n=8), (C-IT: Conventional intensive tillage, C-NT: Conventional no tillage, O-IT: Organic intensive tillage, O-RT Organic reduced tillage). Capital letters indicate significant differences among production system and lower case significant differences between cover crop treatments within each production system (Tukey-Test, α = 0.05, for statistical output see Table 2).

**Table 2 I Statistical ANOVA output for the assessed variables in winter wheat and maize.** ($F_{(df1,df2)}$ values and significance level; df1: numerator degrees of freedom; df2: denominator degrees of freedom; ns: non-significant; ° p<0.1; * p<0.05; ** p<0.01; *** p<0.001). NeffCC: N effect of cover crop (see equation (3)). Significant effects of the various factors and treatments are in bold.

| Crop | Parameter | Experiment (E) | Block (E:B) | P. system (PS) | cover crop (CC) | PS x CC |
|---|---|---|---|---|---|---|
| Wheat | Yield | ns | ns | **33.0**$_{(3,21)}$ *** | **3.6**$_{(3,84)}$ * | ns |
| | Nconcentration | **299.6**$_{(1,21)}$ *** | **4.0**$_{(6,21)}$ ** | **37.4**$_{(3,21)}$ *** | ns | ns |
| | Nuptake | **26.1**$_{(1,21)}$ *** | **4.1**$_{(6,21)}$ ** | **59.4**$_{(3,21)}$ *** | ns | ns |
| | NeffCC | ns | ns | ns | **2.4**$_{(3,84)}$ ° | ns |
| | Weed cover in crop | ns | ns | **6.5**$_{(6,21)}$ ** | **7.4**$_{(3,84)}$ *** | **4.3**$_{(9,84)}$ *** |
| | Cover crop biomass | **154.9**$_{(6,21)}$ *** | **3.2**$_{(3,21)}$ * | ns | **37.9**$_{(3,56)}$ *** | ns |
| | Weed biomass in CC | **43.9**$_{(6,21)}$ *** | **3.1**$_{(6,21)}$ * | ns | **45.6**$_{(3,84)}$ *** | ns |
| Maize | Yield | **29.3**$_{(1,21)}$ *** | ns | **75.3**$_{(3,21)}$ *** | **30.7**$_{(3,84)}$ *** | **2.7**$_{(9,84)}$ ** |
| | Nconcentration | **318.8**$_{(6,21)}$ *** | **2.2**$_{(3,21)}$ ° | **60.9**$_{(6,21)}$ *** | **53.1**$_{(3,84)}$ *** | **2.1**$_{(9,84)}$ * |
| | Nuptake | **113.5**$_{(1,21)}$ *** | ns | **120.0**$_{(3,21)}$ *** | **43.2**$_{(3,84)}$ *** | **2.1**$_{(9,84)}$ * |
| | NeffCC | ns | ns | ns | **43.2**$_{(3,84)}$ *** | **2.0**$_{(9,84)}$ * |
| | Weed cover in crop | ns | ns | **104.6**$_{(6,21)}$ *** | ns | ns |
| | Cover crop biomass | **54.4**$_{(6,21)}$ *** | ns | **3.5**$_{(6,21)}$ * | **127.3**$_{(3,56)}$ *** | ns |
| | Weed biomass in CC | **35.9**$_{(6,21)}$ *** | ns | ns | **41.9**$_{(3,84)}$ *** | ns |

Cover crop effects on yield were much higher for maize. Maize yield was increased after the legume cover crop (hairy vetch), compared to bare fallow, in all tested production systems, having 61%, 27%, 14%, and 8% higher yields in O-RT, O-IT, C-NT and C-IT, respectively (Figure 1 and 2). This increase was significant in all systems except C-IT. In contrast, the non-legume cover crop (white mustard) had no significant impact on yield but showed differential effects depending on the cropping systems. Maize yield was not affected by white mustard in the conventional systems. It negatively affected yield in the O-IT system and caused slightly higher yields in the O-RT system. The significant interaction term between production system and cover crop treatment for maize yield (Table 2) further showed that cover crop effects were production system dependent.

Figure 2 shows the mean response ratio of cover cropping compared to bare fallow for each of the four cropping systems. Overall, this ratio tended to increase along the management intensity gradient, being lowest in the most intensively managed system (C-IT) and highest in the most extensively managed system (O-RT). This observation was more pronounced for maize and was mainly driven by the legume and mixture cover crop treatments (Figure 2).

The addition of cover crops also altered the yield gap between the four production systems, as illustrated in Figure 3. For instance, average yield in the conventional production system without tillage was comparable to the intensive tilled system when legume based cover crops (legume and mixture treatments) were present. However, in absence of cover crops, average yield was 10% lower in the system without tillage. Similarly, crop yield in the organic production system with reduced tillage was comparable to the intensively tilled organic system when cover crops (especially legumes) were present. However, in absence of cover crops, crop yield in the organic reduced tillage system was 23% and 33% lower than in the tilled organic systems for wheat and maize, respectively. Overall, cover cropping effects decreased with increasing management intensity.

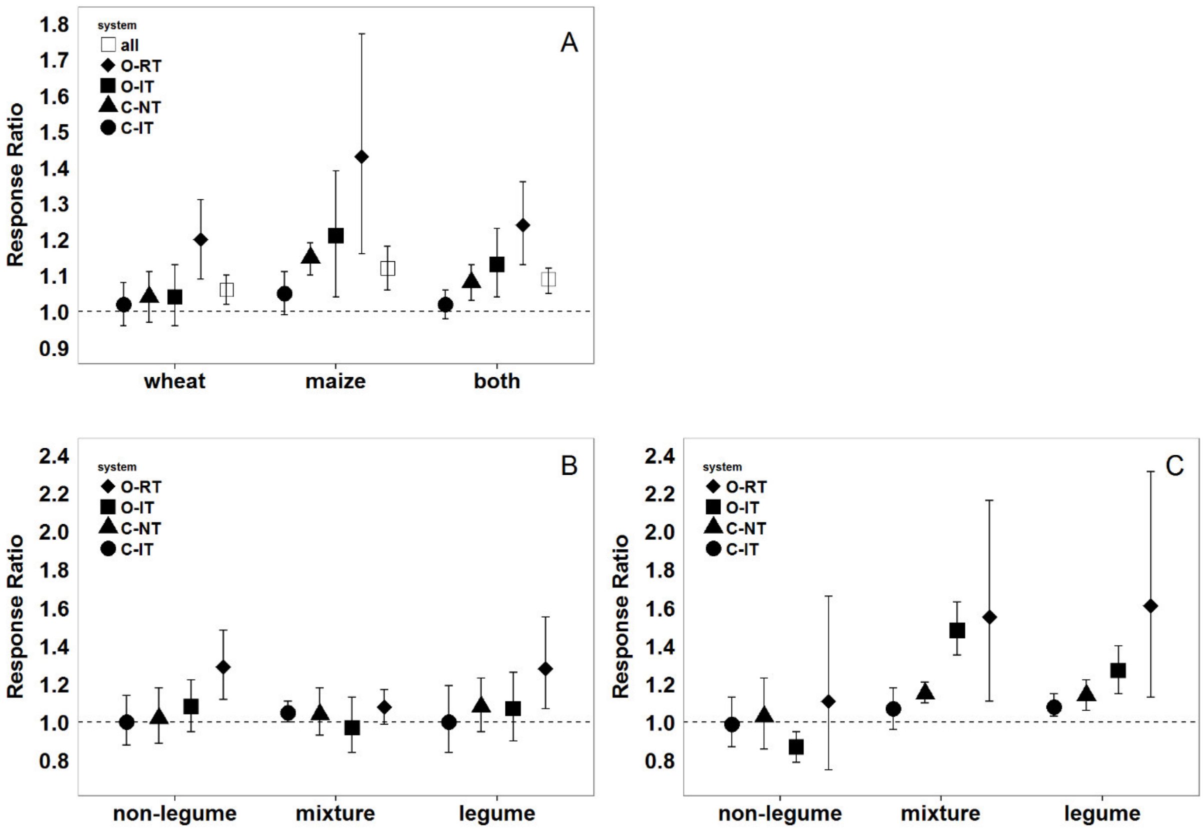


**Figure 2 | Cover cropping to bare fallow yield response ratio in the different production systems for both crops together (A) and for wheat (B) and maize (C)** (C-IT: Conventional intensive tillage, C-NT: Conventional no tillage, O-IT: Organic intensive tillage, O-RT Organic reduced tillage). Mean response ratios and 95% confidence intervals (CI) are shown (n=8). Means are considered significantly different from bare fallow if their CIs are not overlapping 1.

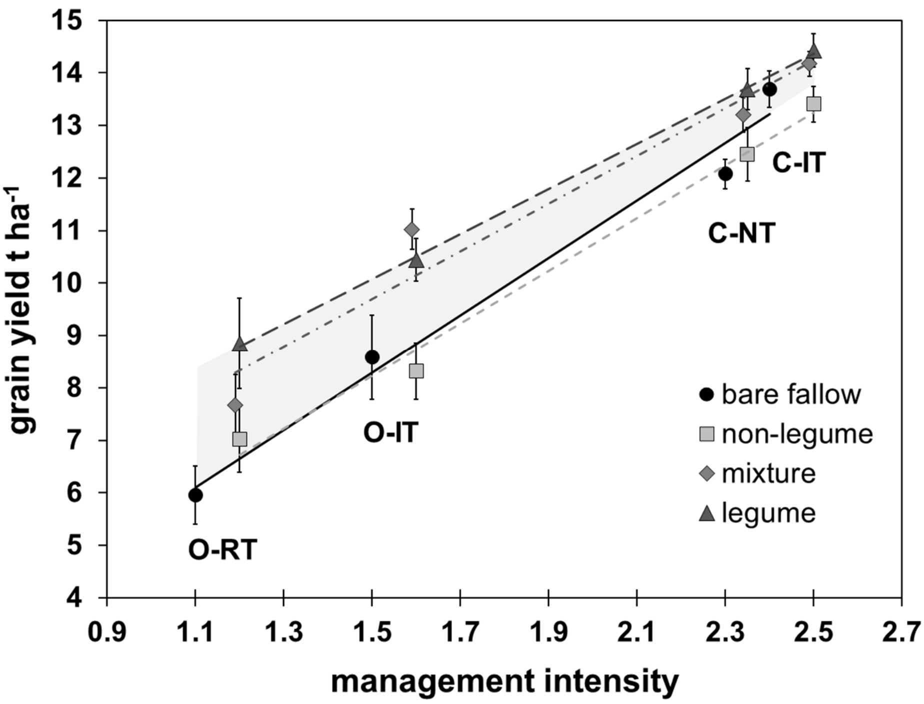


**Figure 3 | Grain yield (sum of wheat and maize) as a function of management intensity (production system) and cover crop treatments** (Mean ± standard errors, n=8). The management intensity is derived from Table 1. The grey area shows the potential of cover crops for ecological intensification for each of the four production systems as a function of decreasing management intensity.

### *Effects of production system and cover crop on weeds*

The addition of cover crops significantly reduced weed biomass during the fallow period for each of the cover crop treatments (Table 2), and cover crop biomass was negatively correlated with weed biomass (Figure 4). The higher the cover crop biomass, the less weeds could establish, regardless of whether the cover crops were growing short-term (before wheat) or long-term (before maize). Weed reduction reached 50% efficiency with a cover crop biomass production of at least 1.7 t $ha^{-1}$.

Decreased weed biomass during the cover cropping period did not necessarily result in decreased weed pressure in the following main crop. In contrast, cover crop treatments had only a small impact on the weed pressure in the main crops, and weed cover at the critical main crop growth stage depended on the production system (Table 2). While weeds could be successfully controlled with herbicides in the conventional systems (less than 10% cover) and relatively well supressed through intensive tillage in the organic system (17% cover over both crops), weed cover was much higher in the organic reduced tillage system (23% soil cover in winter wheat and 35% cover in maize) (see Supplementary Fig. S2 online). However after the white mustard cover crop treatment, which produced the most biomass, weed cover at the critical growth stage was significantly reduced for winter wheat in the O-RT system ($F_{3,21}$= 6, p<0.01, see Supplementary Fig. S2 online). The significant interaction between production system and cover crop treatment on weed cover in wheat (Table 2) also showed that cover crop effects on weeds depended on the production system. In contrast, no differences in weed cover were observed between cover crop treatments in maize for any of the four production systems (see Supplementary Fig. S2 online).

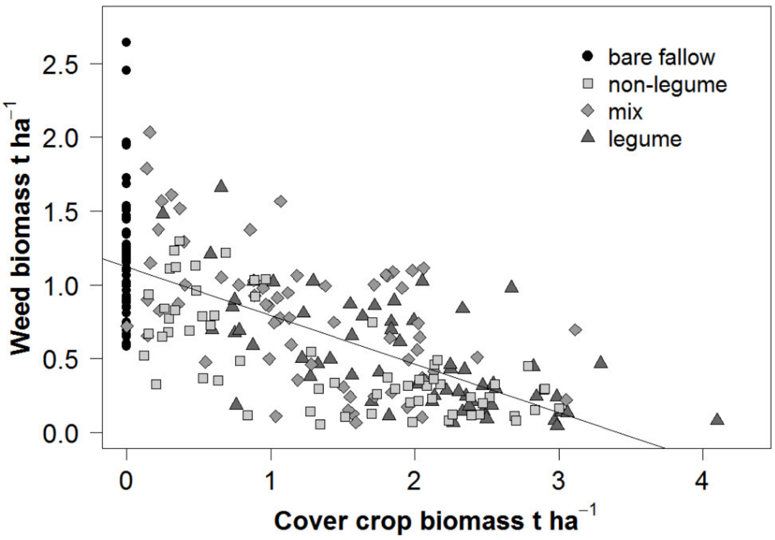


**Figure 4 I Linear correlation between cover crop biomass and weed biomass.** (All data, n=256, $r^2$ = 0.48, p < 0.001).

### *Effects of production system and cover crop on crop nutrition*

Main crop N content was significantly influenced by production system and cover crop treatments (Table 2). Both grain N concentration and N content were higher in the conventional systems and were generally positively affected by the legume cover crop treatment and the cover crop mixture treatment, which also included legumes (see Supplementary Table S3 online). Maize N uptake was strongly affected by the cover crop treatment, while effects on wheat were negligible (Table 2). In order to assess the contribution of cover crops for crop N uptake, a cover crop N effect ($N_{effCC}$) was computed (see equation (3) in the methods). Averaged across all production systems and compared to bare fallow, the inclusion of the legume cover crop or the cover crop mixture increased maize N uptake ($N_{effCC}$) by 32 kg ha$^{-1}$ and 28 kg ha$^{-1}$, respectively. The non-legume cover crop did not affect N uptake

(0 kg ha$^{-1}$), and the N effect was even negative (not significant) in the ploughed systems (C-IT, O-IT). Legume and mixture cover crop effects on maize N uptake were strongest in the organic systems (O-IT: 27.8 kg N ha$^{-1}$, SE: ± 5.4; O-RT: 22.4 kg N ha$^{-1}$, SE: ± 5.4, n=8) and decreased within the conventional systems, being intermediate in the C-NT (18.2 kg N ha$^{-1}$, SE: ± 4.2, n=8) system and lowest in the C-IT system (10.8 kg N ha$^{-1}$, SE: ± 3.2, n=8) (Figure 5; results for the wheat are shown in the Supplementary Fig. S3 online). $N_{effCC}$ was positively correlated with maize yield in all production systems. However, the amount of variance explained by the N effect of cover crops decreased along the management intensity gradient, being highest in O-RT and lowest in C-IT (O-RT: $r^2$=0.73***; O-IT: $r^2$=0.59***; C-NT: $r^2$=0.53***; C-IT: $r^2$=0.29**, see Supplementary Figure S4 online).

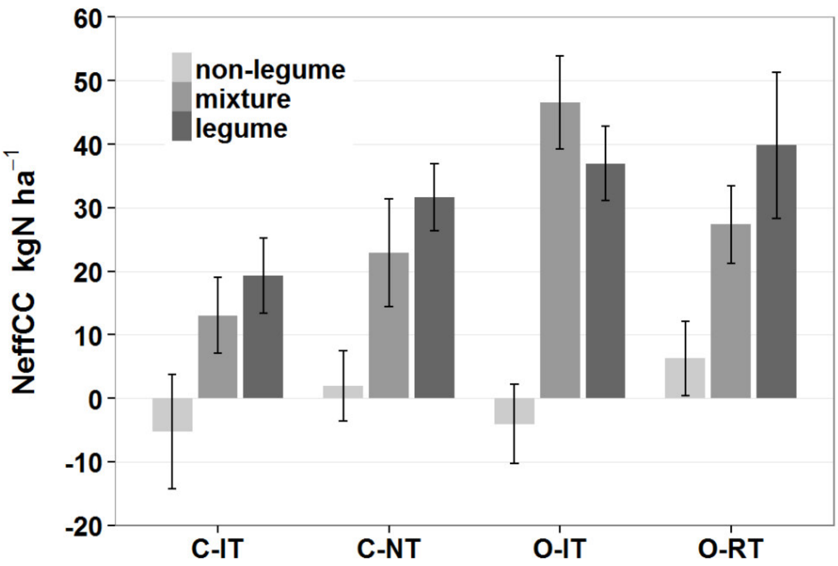


**Figure 5 I N effect from cover crop on the N uptake of maize (NeffCC) in the different production systems.** (mean ± standard errors, n=8, NeffCC calculation see equation (3)), (C-IT: Conventional intensive tillage, C-NT: Conventional no tillage, O-IT: Organic intensive tillage, O-RT Organic reduced tillage).

Analysis of $^{15}N$ natural abundance levels in the legume (hairy vetch) and the non-legume (white mustard) cover crop treatments preceding maize indicated that in hairy vetch, 89% of plant N was derived from biological nitrogen fixation. This corresponds to an additional above ground N input of 94 kg N ha$^{-1}$ (see Supplementary Table S4 online).

Across all treatments in this experiment, available N supply correlated strongly with yield and explained 48% of the variation in crop yield (Figure 6). N supply was a function of fertilisation level (supplied available N) and included an estimation of additional N provided by legume cover crops (see methods). The relationship between crop yield and weed cover was weaker and explained only 29% of variance (Figure 6), indicating that N availability was the main driver of crop yield in the experiment.

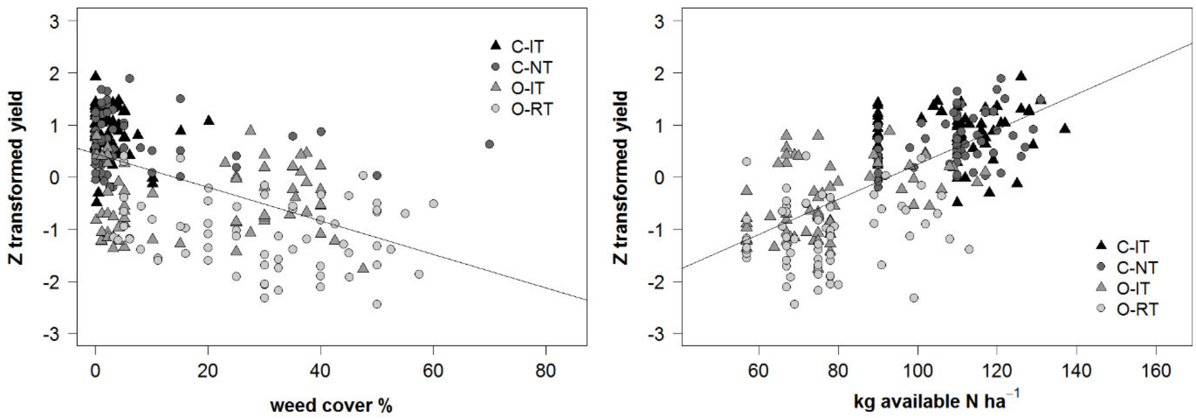


**Figure 6 I Correlations between the standardized yield of wheat and maize and weed cover ($r^2$=0.29***) and N supply ($r^2$=0.48***).** Yield values for wheat and maize were standardized across both experiments (FAST I and FAST II) using the z-score to evaluate general effects independently from yield differences among crops and experiments (see materials and methods for N supply estimation). C-IT: Conventional intensive tillage, C-NT: Conventional no tillage, O-IT: Organic intensive tillage, O-RT Organic reduced tillage.

### *Cover crop growth and biomass production*

The legume cover crops, common vetch (before wheat) and hairy vetch (before maize), showed the most stable development across experiments and years (see Supplementary Fig. S5 online). Both vetch species covered the soil rapidly and reached a high soil cover (on average over 80% soil cover at 60 days after sowing) before wheat and maize. In contrast, white mustard, the non-legume cover crop, showed the highest variation in terms of establishment and growth. White mustard emerged and covered the soil rapidly in the first year of the rotation before wheat (averaged across both experiments over 70% soil cover at 40 days after sowing) but failed before maize in both experiments (less than 20% soil cover at 60 days after sowing). Although emergence was also rapid, further development stopped approximately 25 days after sowing (see Supplementary Fig. S5 online).

Biomass production differed significantly between cover crop treatments (Table 2). In the first cover cropping period before wheat, white mustard produced the most biomass (2.2 t ha$^{-1}$), followed by common vetch (1.5 t ha$^{-1}$), and the cover crop mixture (0.9 t ha$^{-1}$) (averaged across both experiments). In the second cover cropping period before maize, hairy vetch and the cover crop mixture produced the most biomass (2.4 and 1.6 t $ha^{-1}$, respectively), while white mustard only produced 0.7 t $ha^{-1}$.

**Discussion**

Conservation agriculture and organic farming are recognized as valuable strategies to mitigate the negative environmental impacts of arable production. However, in Europe, both systems generally achieve less yields than conventional intensive agriculture, and although adoption of both practices shows a positive trend, arable land under conservation and organic agriculture is, for both systems, less than 5% (FAOstat, 2016). The main reasons for this yield gap are difficulties related to weed control and insufficient or asynchronous nutrient availability. Our study confirms this, as yield was highest in the C-IT system and decreased steadily in C-NT, O-IT, and O-RT. The main drivers of the yield decrease were reduced nitrogen availability and increased weed infestation.

Our results demonstrate that cover crops can be used to reduce the yield gap between organic arable farming and conventional farming and between conservation agriculture and intensive tillage. Our observations, thus, confirm the findings of Pittelkow *et al.* (2015a), who showed the crucial importance of crop rotation and residue management under no tillage. Moreover, the inclusion of nitrogen fixing cover crops in the organic production systems led to increased yields and could substantially contribute to decrease the yield gaps compared to the conventional systems. In the organic intensively tilled system, yield differences between conventionally managed plots were reduced from -37% without cover crop to -19% with the use of cover crop mixtures. This confirms the statement of Ponisio *et al.* (2015) that diversification practices, such as the use of cover crops to extend the crop rotation, can reduce the yield gap between organic and conventional production. The positive effect of crop rotation diversification with cover crops on maize yield was also shown in a long-term trial in the USA in both organic and integrated management (Snapp *et al.*, 2010).

A wide range of studies have demonstrated that cover crops provide numerous ecological services including improved crop nutrition, reduced nutrient leaching losses, and enhanced soil and water protection (Drinkwater *et al.*, 1998; Dabney *et al.*, 2001; Hartwig and Ammon, 2002; Thorup-Kristensen *et al.*, 2003). However, so far it was unclear to what extent the positive effects of cover crops on yield depended on the production system, as few replicated field experiments have directly addressed this question. Earlier studies investigated the effects of cover crops in different crop rotations (Doltra and Olesen, 2013), with different tillage strategies (Armengot *et al.*, 2015; Halde *et al.*, 2015), or when fertilizer input varied (Miguez and Bollero, 2005; Tonitto *et al.*, 2006; Gabriel and Quemada, 2011). Our study design enabled us to investigate the magnitude of cover crop effects between highly different production systems. The overall cover crop effect was highest in the O-RT system (+24%), lowest in the C-IT system (+2%), and intermediate in the O-IT (+13%) and C-NT (+8%) systems. Thus, the cover crop effects reflected the management intensity gradient.

Cover crop effects in wheat were only significant in the O-RT system, with the lower management intensity and greater weed reduction likely responsible for the increased wheat yield after the non-legume cover crop. Although it is difficult to separate the various factors that influence yield, it seems that the additional N input by the legume cover crops also compensated for enhanced weed competition in the O-RT system. Indeed, wheat yield after the legume cover crop was equal to that of the non-legume cover crop, despite higher weed cover in this treatment. Moreover, although no differences in weed cover between different cover crop treatments were observed in maize, significantly higher yields were achieved after the legume and mixture cover crops, which support the previous observation.

Biological nitrogen fixation by legume cover crops is likely to be the main mechanism responsible for enhanced maize yield, as both cover crop treatments with legume species (mixture and legume) significantly increased maize yield over the four production systems. This confirms earlier findings that N-demanding crops, such as maize, can greatly profit from additional N input by legume cover crops (Thorup-Kristensen *et al.*, 2003; Tonitto *et al.*, 2006; Cavigelli *et al.*, 2008; Snapp *et al.*, 2010; Gabriel and Quemada, 2011; Tosti *et al.*, 2012; Gentry *et al.*, 2013). The choice of an overwintering legume cover crop also contributed to higher cover crops effects on maize than on wheat, as the growing period of the cover crop before maize was more than twice as high. One of the great advantages of legume cover crops is that their C/N ratio is low so that residues are easily decomposed, thus releasing N rapidly (Drinkwater *et al.*, 1998; Thorup-Kristensen *et al.*, 2003). Although we did not directly assess the recovery of cover crop or fertilizer N in the main crop, we observed that across all systems approximately 25% of main crop N uptake was derived from the introduction of the legume cover crop. Gentry *et al.* (2013) investigated the impact of a red clover cover crop on corn in conventional, integrated and organic systems and showed that the N credit of red clover on corn was about 40 kg N $ha^{-1}$, which is similar to our results (NeffCC from 19 to 40 kg N $ha^{-1}$). The main difference with our study is that Gentry did not find differences in the magnitude of the N credit between the different management systems they studied. However, no mineral N fertilizer was applied to corn in that study, which could explain why N credit was similar across the systems.

Our results confirm that weed control is a major issue in organic farming, especially under reduced tillage where weed pressure was high. Thus, cover crop management is an important tool in such systems, as it can help to reduce weed pressure, and additional N input by legume species can decrease the competition between weeds and crops for nutrients. This was also observed by Cavigelli *et al.* (2008), who found that N limitation was more important than weed competition when explaining the yield gap between organic and conventional systems. Our results are also in agreement with results from another long-term experiment in Switzerland in which reduced tillage and conventional tillage are compared under organic farming practices. In that experiment, yield in the reduced tillage system was similar or even higher compared to the organic ploughed system. This was due, in part, to the sowing of a legume cover crop (pea) before maize in the reduced tillage system; whereas the cover crop was absent in the ploughed system (Krauss *et al.*, 2010). However, weed abundance was 2.3 times higher under reduced tillage in that experiment (Armengot *et al.*, 2015).

The success of cover crops largely depends on proper establishment and biomass production. Several studies showed that weed suppression by cover crops is strongly related to biomass production and early soil cover of the cover crops (Teasdale, 1996; Dorn *et al.*, 2015). In this study, cover crop success varied greatly across years and experiments, except for the treatment with legume cover crops, which yielded the highest biomass and had lowest yield variability across both years. In contrast, biomass production of the non-legume cover crop was variable, and white mustard did not grow well in the second year of either experiment before maize. Interestingly, more than 80% of the accumulated N in hairy vetch (legume cover crop treatment) was derived from biological nitrogen fixation, suggesting that N availability was low and may explain the reduced growth of white mustard. Moreover, white mustard has a low frost tolerance and was killed during winter, in contrast to hairy vetch, which could continue to grow in the spring.

This study focused on the direct short-term effects of cover cropping on crop yield under a single environment. Whereas cropping system effects on yield are highly influenced by environmental factors (Pittelkow *et al.*, 2015b), our study enabled us to compare cover crop effects in the different system without this constraint. Thus, we believe that increasing cover crop effects as a function of management intensity should be given greater consideration in the development of cover cropping systems.

In conclusion, our study demonstrates that: i) cover crop effects vary between production systems, ii) that positive effects of cover crops on productivity increase when management intensity is reduced, iii) that cover crop functional groups (legume versus non-legume) have different effects depending on cover cropping length and succeeding main crop, as well as on the production system, and iv) that cover crops are essential to maintain a certain yield level when soil tillage intensity is reduced and/or production converted to organic agriculture. The inclusion of cover crops in the rotation thus provides additional opportunities to increase the yields of production systems with lower management intensity.

## Materials and methods

### *Farming System and Tillage experiment (FAST)*

The FAST experiment compares the main arable farming systems in Switzerland, namely conventional and organic farming systems, with different tillage intensity for 6-year crop rotation cycles. In Swiss conventional farming, synthetic fertilizers and pesticides are used for crop nutrition and protection, in contrast to organic farming in which both are prohibited. The conventional systems in FAST are managed according to the “Proof of Ecological Performance” (PEP) guidelines of the Swiss Federal Office for Agriculture. The “PEP” is based on standards for integrated production with requirements for an even nutrient balance, a regular crop rotation, suitable soil protection, and targeted use of plant protection products (FOAG, 2014). Farmers need to follow these guidelines in order to receive direct payments from the government. In 2014, 88% of recorded Swiss farms were registered into “PEP”. The organic systems are managed according to Bio Suisse guidelines, the governing body for organic producers in Switzerland (Bio Suisse, 2016).

The field site is located at the Swiss federal agricultural research station Agroscope, Reckenholz near Zurich (latitude 47°26'N, longitude 8°31'E). The soil type at the experimental site is a calcareous Cambisol and contains on average 1.4% soil organic carbon (SOC), 23% clay, 34% silt, 43% sand, and had a pH($H_2O$) of 7.3. The field site used for this experiment has been cultivated according to Swiss organic standards since 2002, meaning that the organically managed systems experienced no conversion from conventional to organic farming. The long-term (1981-2010) average annual precipitation was 1054 mm, with a mean annual temperature of 9.4°C (Swissmeteo). FAST is composed of two field experiments established on the same field beside each other (see Supplementary Fig. S1). The first experiment started in summer 2009 (FAST I) and the second in summer 2010 (FAST II), following a staggered start design. Both experiments comprise the following factors: i) production system treatment (conventional intensive tillage (C-IT), conventional no tillage (C-NT), organic intensive tillage (O-IT) and organic reduced tillage (O-RT)) and ii) cover crop treatment (no cover crop as control (C), legume (L), non-legume (NL) and a mixture of several cover crops (M)). This resulted in a total of 16 treatments each replicated four times. The 64 plots for FAST I and FAST II were arranged according to a split-plot design with randomized complete blocks. Each production system (C-IT, C-NT, O-IT, and O-RT) represented a main plot within blocks (see Supplementary Fig. S1 online). These main plots were each subdivided in four split-plots for the factor cover crop. The size of the main plots was 6 m x 30 m, allowing the use of standard farming equipment. The size of a subplot, which included one cover crop treatment, was 3 m x 15 m. All assessments were performed within the inner 2 m x 10 m of each subplot to avoid border effects.

*Crop rotation*

Before the start of each of the two experiments, the whole experimental area was ploughed and forage pea (*Pisum sativum* L. subsp. *arvense*) was grown as a pre-crop. Subsequently, the experiment started and the following crop sequence implemented using a six-year crop rotation: winter wheat (year 1), maize (year 2), field bean (year 3), winter wheat (year 4), and a grass-clover mixture (year 5 and 6). In the first year of the experiment, cover crops were sown as a short intercrop in the middle of August (see Supplementary Table S1) before sowing of winter wheat (*Triticum aestivum* L. cv. 'Titlis'). After harvesting winter wheat, cover crops were sown again (see Supplementary Table S1) as a long intercrop before the maize crop (*Zea mays* L. cv. 'Padrino'). The cover crop treatments consisted of a non-legume (NL) (white mustard, *Sinapis alba*), a legume (L) (common vetch (*Vicia sativa*) before winter wheat and hairy vetch (*Vicia villosa*) before maize), and a cover crop mixture (M) (the mixture UFA-Alpha supplied by UFA-Samen AG containing phacelia (*Phacelia tanacetifolia*), Persian clover (*Trifolium resupinatum*) and berseem clover (*Trifolium alexandrinum*) before winter wheat and a self-designed mixture (SM-ART) containing phacelia, hairy vetch, buckwheat (*Fagopyrum esculentum* Moench) and camelina (*Camelina sativa* L.) before maize). For the main crops, seeds coated with "Coral extra" (Sygenta AG) for wheat and "TMTD 98% Satec" (Bayer AG) for maize were sown in the conventional plots. Untreated seeds were sown in the organic plots, and all seeds were certified. Except for the winter wheat straw, which was removed from the field as is common practice in Switzerland (often used as litter for animal production), all other crop residues (cover crops and maize) remained on the plots. The experiment is ongoing. The second crop rotation began for FAST I in autumn 2015 and will begin in autumn 2016 for FAST II.

*Soil Tillage and sowing*

Primary tillage in the intensive tillage treatment (IT) in both organic and conventional systems was performed with a mouldboard plough (Menzi, B. Schnyder Pflugfabrik, Brütten, Switzerland) to a target depth of 20 cm. This practice is common in Switzerland and most parts of Europe. Subsequently, the seedbed was prepared with a rotary harrow to a depth of 5cm (Amazone, H. Dreyer GmbH & Co. KG, Hasbergen, Germany) just before sowing. The soil-conservation tillage treatment differed between the conventional and organic systems. In the conventional system, no soil tillage operations were conducted during the whole experimental period, corresponding to no tillage production (NT). Crops were seeded directly into the soil, either with a no-till cereal seeder (Direttissima 250, Gaspardo, Pordeone. Italy) or with a no-till single-grain seeder for maize (Amazone, H. Dreyer GmbH & Co. KG, Hasbergen, Germany). Soil operations in the organic reduced tillage (RT) treatment were performed to a target depth of 5 cm with a disk harrow (Haruwy, Lausanne, Switzerland) before wheat and a rotary harrow before maize. Before sowing of the cover crops, a shallow (5cm depth) tillage operation was performed with a rotary tiller (Amazone, H. Dreyer GmbH & Co. KG, Hasbergen, Germany), except for the C-NT system in which cover crops were sown directly. Dates of soil tillage operations as well as sowing dates of the crops are given in the supplement (see Supplementary Table S1 online).

*Fertilization*

Fertilization in the conventional plots was exclusively mineral, and the amount of nitrogen (N) applied was in accordance with the Swiss guidelines for fertilization(Flisch *et al.*, 2009). Winter wheat and maize received 110 kg N $ha^{-1}$ and 90 kg N $ha^{-1}$, respectively. In addition to N fertilization, phosphorous (P) and potassium (K) were regularly added in the form of $P_2O_5$ and $K_2O$, respectively to balance nutrient export by harvested grain and straw (in total 116 kg P $ha^{-1}$ and 138 kg K $ha^{-1}$ for the winter wheat and maize crops, respectively).

The organic plots were fertilized with cattle slurry at a target level of 1.4 livestock units $ha^{-1}$. The slurry was purchased from an organic farmer near the experimental site. Winter wheat received a total of 60 $m^3$ $ha^{-1}$ slurry in two applications of 30 $m^3$. Likewise, 70 $m^3$ $ha^{-1}$ slurry was applied in two applications (40 and 30 $m^3$ $ha^{-1}$) in the maize crop. Organic winter wheat received, averaged across both experiments, a total of 119 kg N $ha^{-1}$ (45 kg of slurry N was in the form of directly plant available $NH_4^+$), and maize received 132 kg N $ha^{-1}$ (68 kg of slurry N was in the form of $NH_4^+$). Application dates and the total amounts of applied N are described in the supplement (see Supplementary Table S1 online). Moreover, we performed an estimation of available N supply by fertiliser and legume cover crops. For the conventional systems N supply from fertiliser (Nfert) corresponded to total synthetic mineral N input. Available N from the slurry (Nfert) in the organic systems is calculated as follows:

$$Navailable = a \times (NH_4\text{-}N) + b \times (Total\ N - NH_4\text{-}N) \qquad (1)$$

Where a (0.8) is the $NH_4$-N volatilization coefficient and b (0.35) the proportion of organic N mineralized from the cattle slurry(Cavigelli *et al.*, 2008). Finally, an estimation of available N derived from the legume cover crops (NfCC) was determined as follows:

*NfCC = 0.3 x Ndfa* (2)

Where 0.3 is the proportion of organic N mineralized from the cover crop aboveground biomass and Ndfa the amount of fixed atmospheric N by the cover crops. Ndfa values were determined either from $^{15}N$ analysis for hairy vetch preceding maize (see below) or calculated with values determined by Büchi et al.(Büchi *et al.*, 2015) for the common vetch (legume treatment) and the two clover species preceding wheat. The addition of Nfert and NfCC represent the total N supply.

*Weed management*

Weeds in the conventional plots were managed with post-emergence herbicides, and mechanical control measures were implemented in the organic plots. In the C-NT treatment, Glyphosate (Glyphosat 360S, Schneiter Agro AG, Switzerland) was additionally applied before sowing of the main crops either to kill natural vegetation (weeds) or the cover crops. The natural vegetation and the cover crops in the other systems were terminated by tillage. For the organic systems, weeds in winter wheat were controlled by a harrow (Lely Holding S.à.r.l, Maasluis, The Netherlands) and by a star cultivator (Haruwy, Lausanne, Switzerland) in maize. Application dates and the number of weed control operations are described in the supplement (see Supplementary Table S1 online).

***Plant analysis***

The grain yield of winter wheat was determined by harvesting the middle 8 rows of each subplot over a length of 10m with a plot-sized combined harvester (1.33m width). For maize, the grain yield was determined based on hand collected cobs that were collected in the middle 2 rows of each subplot over a length of 5m. The overall yields of wheat and maize were relatively low compared to other experiments(Honegger *et al.*, 2014) and average yields obtained in Switzerland(FAOstat, 2016). This can be partly explained by two weather events. In 2010, unsuitable weather conditions delayed the harvest and a storm led to lodging of wheat, which caused, mainly in the conventional plots, at least a 10% yield loss. In July 2011, a hail event led to a wheat yield loss of 15% in organic and 20% in conventional plots in FAST II, as well as an 18-20% maize yield reduction in FAST I (estimates made by hail insurance experts).

Cover crop biomass was determined by collecting the plants within two 0.25m$^2$ frames (50cm x 50cm) per subplot before winter onset. For all plant material, dry weight was determined and yield calculated to ton dry weight per hectare. The harvest dates are provided in the Supplementary Table S2. In addition, plant material was ground and the nitrogen concentration of wheat and maize grains determined using elemental analysis by the Dumas method(2014).

In order to assess the contribution of cover crops to N nutrition of the succeeding main crop, a N effect of  cover crops (NeffCC) was calculated after Tosti et al. (2012):

*NeffCC,i = NuptCC,i - NuptCtr* (3)

where NuptCC,i is the N uptake of the main crop after a cover crop treatment and NuptCtr is the N uptake of the main crop after the control treatment without cover crops.

Atmospheric nitrogen fixation by legume cover crops was determined with the natural abundance method(Unkovich *et al.*, 2008). The relative abundance of the nitrogen isotope $\delta^{15}N$ was determined on ground samples of aboveground biomass from the legume and the non-legume cover crop treatments preceding the maize main crop. This was done using mass spectrometry for $\delta^{15}N$ determination at the stable isotope facilities of the University of Saskatchewan in Canada. The percent N derived from atmosphere (abbreviated as: %Ndfa) was calculated as follows:

$$\%Ndfa = (\delta 15N\ reference\ plant - \delta 15N\ legume) \div (\delta 15N\ reference\ plant - B) \times 100 \quad (4)$$

%Ndfa values were calculated using the $\delta^{15}N$ value of the non-legume cover crop (Brassica) (reference cover crop) growing in the same main plot as the legume cover crop. The B-value for hairy vetch (-0.35) was taken from a study that examined the atmospheric nitrogen fixation of different legume cover crops in Switzerland (Büchi *et al.*, 2015). The total amount of N fixed from the atmosphere was then obtained by multiplying aboveground N uptake with %Ndfa.

***Weed assessment***

Weed cover was assessed for winter wheat at critical growth stage BBCH 25 (tillering) and for maize at critical growth stage BBCH 18 (8 leaves unfolded). The percentage of soil covered by weeds was visually estimated by averaging weed cover in two 1 $m^2$ frames located in the middle part of each subplot. Moreover, the growth of the cover crop and their ability to control weeds was assessed using the same protocol and estimating the percentage of soil covered by cover crops and weeds at regular intervals during the cover cropping period. Additionally, cover crop and weed biomass was determined by collecting the biomass within two 0.25$m^2$ frames (50cm x 50cm) per subplot. Weed and cover crop species were sorted for each sample before dry weight determination. For all weed assessments, mean values were calculated for each subplot and used for the analysis. An overview of the assessment dates and corresponding crop stages is given in the supplement (see Supplementary Table S1 online).

***Statistical analysis***

Statistical analyses were all performed using R(R Core Team, 2020). Variance analyses on the assessed variables were performed using a split-plot design with “production system” (C-

IT, C-NT, O-IT, O-RT) as main plot and “cover crop” (C, NL, L, M) as subplot in an ANOVA. The terms “experiment” and “replicate blocks within experiment” were included first in the model to account for their variation. Production system, cover crop treatment and their interactions were considered as fixed effects. The weed cover data were root square transformed prior to analysis to meet analysis assumptions. For graphical visualisation, original data are plotted. Significant differences among factor levels were determined by a post-hoc test (Tukey’s HSD test) with the R-package TukeyC (Faria *et al.*, 2014) allowing the test to be performed with multiple error terms (main plot error for system and subplot error for cover crop). The Tukey’s HSD test was also used to test for differences among cover crops within each system. In order to assess the effect size of cover cropping on yield among both crops and the four production systems, bare fallow to cover crop mean response ratios were calculated, as well as their 95% confidence interval (CI) values, with the meta-analysis program OpenMEE (Dietz George *et al.*, 2016). Linear regressions were performed to test for effects of weed and N input on yield. Yield data were standardized per experiment and crop by creating a standardized yield (z-transformation) displaying the number of standard deviations of each observation above or below the overall mean using the function “decostand” of the R-package vegan when both crops and/or experiments were analysed together. This made it possible to analyse overall treatment effects irrespective of experiment (year) and crop.

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**Author contributions**

M.H and B.D. initiated the research and experimental design and B.D and W.J. set up the field experiment. B.D was responsible for the FAST experiment until 2011 and R.W since 2012. W.J was the technical manager of the field experiment. W.J., B.D. and R.W have collected the experimental data. R.W and M.H wrote the manuscript and R.W performed the data analysis. All authors read and commented on the manuscript.

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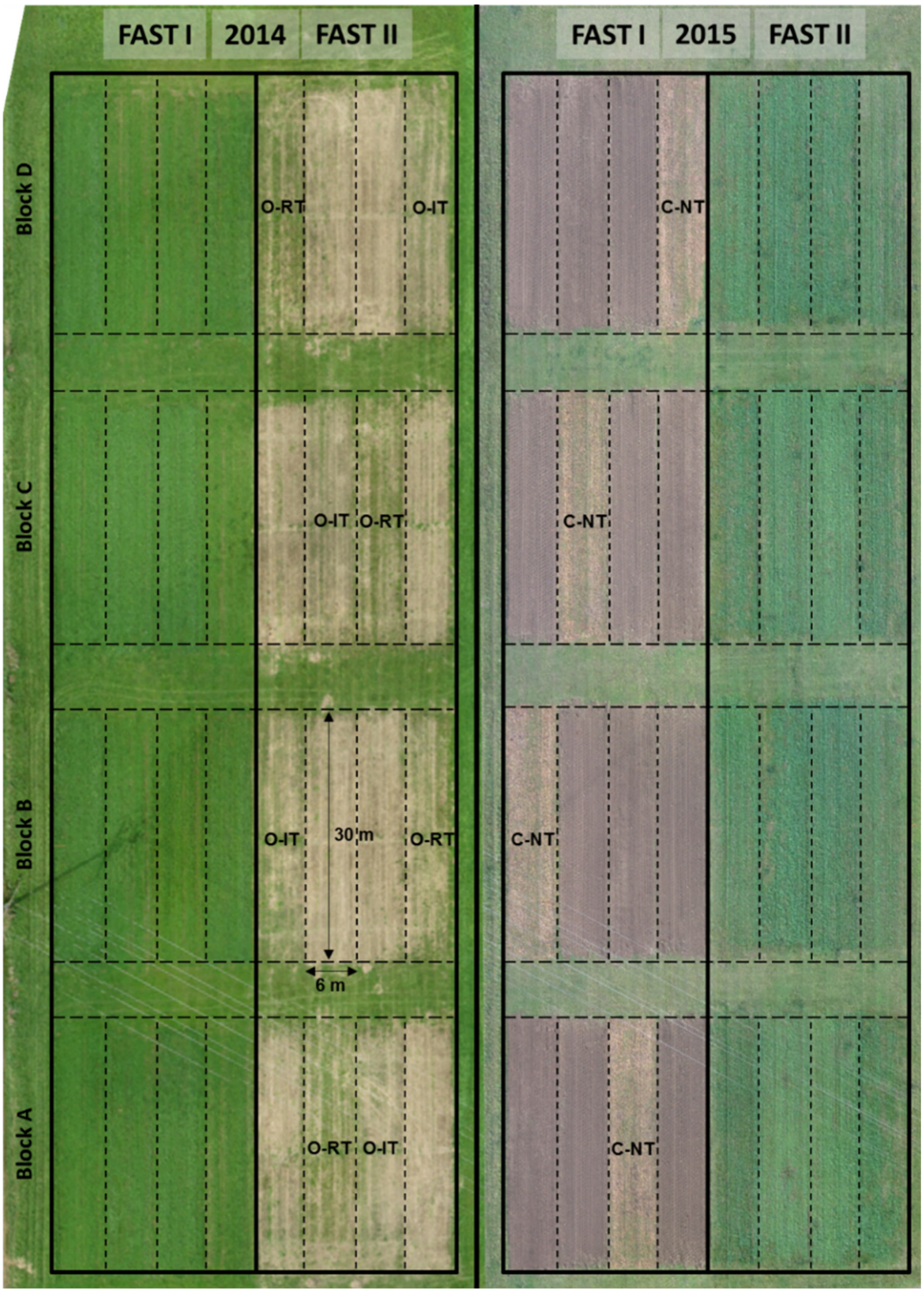
## Supplementary information




**Supplementary Figure S1 I** Aerial pictures of the FAST experiment in August 2014 and in October 2015 (orthomosaics computed from drone imagery (eBee AG, senseFly) with the software Postflight Terra 3D (Pix4D)). The picture in 2014 was taken after winter wheat harvest in FAST II. The crop in FAST I is a grass-clover mixture. The picture in 2015 was taken just after winter wheat sowing in FAST I. The crop in FAST II is a grass-clover mixture. Blocks and main plots (dashed lines) are drawn on the picture. The higher weed infestation in the organic reduced tillage system (O-RT) is well visible in FAST II 2014 and the conventional no tilled (C-NT) plots in FAST I 2015 are also noticeable.

**Supplementary Table S1** I Field operations, N fertilization and weed assessments. (C-IT: conventional intensive tillage, C-NT: conventional no tillage, O-IT: organic intensive tillage, O-RT: organic reduced tillage).

| **Trial** | | **FAST I** | | | | **FAST II** | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Crop** | | **Wheat cv. 'Titlis'** | | **Maize cv. 'Padrino'** | | **Wheat cv. 'Titlis'** | | **Maize cv. 'Padrino'** | |
| | | product / amount | date | product / amount | date | product / amount | date | product / amount | date |
| **Cover crop** | non-legume | White mustard | | White mustard | | White mustard | | White mustard | |
| | legume | common vetch | | hairy vetch | | common vetch | | hairy vetch | |
| | mixture | UFA-Alpha[1] | | SM-ART[2] | | UFA-Alpha[1] | | SM-ART[2] | |
| | sowing | | 24.08.2009 | | 11.08.2010 | | 10.08.2010 | | 11.08.2011 |
| C-IT, O-IT, O-RT | mulching | | 08.10.2009 | | 15.04.2011 | | 08.10.2010 | | 27.04.2012 |
| C-NT | glyphosate | Glyphosat 360S<br>3.5 l ha$^{-1}$ | 09.10.2009 | Glyphosat 360S<br>4 l ha$^{-1}$ | 08.04.2011 | Glyphosat 360S<br>4 l ha$^{-1}$ | 08.10.2010 | Glyphosat 360S<br>4 l ha$^{-1}$ | 17.04.2012 |
| **Tillage** | | | | | | | | | |
| C-IT, O-IT | plough (20cm) | | 08.10.2009 | | 18.04.2011 | | 09.10.2010 | | 28.04.2012 |
| | rotary harrow (5cm) | | 20.10.2009 | | 28.04.2011 | | 11.10.2010 | | 04.05.2012 |
| O-RT | disk harrow (5cm) | | 20.10.2009 | | | | 12.10.2010 | | |
| | rotary harrow (5cm) | | | | 29.04.2011 | | | | 04.05.2012 |
| **Sowing** | | | | | | | | | |
| | date | 400 seed m$^{-2}$ | 21.10.2009 | 9.5 plant m$^{-2}$ | 29.04.2011 | 400 seed m$^{-2}$ | 13.10.2010 | 9.5 plant m$^{-2}$ | 04.05.2012 |
| | row distance | 16.6 cm | | 70 cm | | 16.6 cm | | 70 cm | |
| **Weed control** | | | | | | | | | |
| C-IT, C-NT | | | | | | | | | |
| | herbicide | Azur 3 l ha$^{-1}$ | 25.03.2010 | Mikado 1 l ha$^{-1}$<br>Dasul 1 l ha$^{-1}$<br>Andil 1 kg ha$^{-1}$ | 31.05.2011 | Azur 3 l ha$^{-1}$ | 16.03.2011 | Mikado 1 l ha$^{-1}$<br>Dasul 1.5 l ha$^{-1}$<br>Andil 1 kg ha$^{-1}$ | 31.05.2012 |
| O-IT, O-RT | | | | | | | | | |
| | mechanical 1 | harrow | 27.04.2010 | hoeing | 06.06.2011 | harrow | 16.03.2011 | hoeing | 31.05.2012 |
| | mechanical 2 | | | hoeing | 24.06.2011 | | | hoeing | 20.06.2012 |
| **Harvest (grain)** | | | 04.08.2010 | | 25.10.2011 | | 26.07.2011 | | 22.11.2012 |
| **Fertilization** | | | | | | | | | |
| C-IT, C-NT | | | | | | | | | |
| | Total N (kg N ha$^{-1}$) | 110 | | 90 | | 110 | | 90 | |
| | application 1 | 60 | 19.03.2010 | 30 | 10.05.2011 | 60 | 16.03.2011 | 30 | 08.05.2012 |
| | application 2 | 30 | 09.04.2010 | 60 | 16.07.2011 | 30 | 05.04.2011 | 60 | 15.06.2012 |
| | application 3 | 20 | 17.05.2010 | | | 20 | 09.05.2011 | | |
| O-IT, O-RT | | | | | | | | | |
| | Slurry $N_T$ / $NH_4$-N (kg N ha$^{-1}$)* | 126 / 50 | | 137 / 67 | | 111 / 40 | | 127 / 68 | |
| | application 1 | 30 m$^{-3}$ slurry | 19.03.2010 | 30 m$^{-3}$ slurry | 12.05.2011 | 30 m$^{-3}$ slurry | 16.03.2011 | 30 m$^{-3}$ slurry | 02.05.2012 |
| | application 2 | 30 m$^{-3}$ slurry | 09.04.2010 | 40 m$^{-3}$ slurry | 16.07.2011 | 30 m$^{-3}$ slurry | 05.04.2011 | 40 m$^{-3}$ slurry | 24.05.2012 |
| **Weed assessments** | | | | | | | | | |
| | cover | BBCH 25 | 24.03.2010 | BBCH 18 | 30.05.2011 | BBCH 25 | 15.03.2010 | BBCH 18 | 01.06.2012 |
| | biomass | | 07.10.2009 | | 14.10.2010 | | 04.10.2010 | | 18.10.2011 |

[1] mixture of phacelia (*Phacelia tanacetifolia*), Persian clover (*Trifolium resupinatum*) and berseem clover (*Trifolium alexandrinum*)

[2] self-designed mixture of phacelia, hairy vetch (*Vicia villosa*), buckwheat (*Fagopyrum esculentum* Moench) and camelina (*Camelina sativa* L.)

* $N_T$: N total

**Supplementary Table S2 | Calculations of the management intensity score of the four production systems in FAST** (C-IT: Conventional intensive tillage, C-NT: Conventional no tillage, O-IT: Organic intensive tillage, O-RT Organic reduced tillage). Management intensity is estimated for each production system using three anthropogenic input factors (Energy use, N fertilisation and pesticide). These factors were also used in different studies evaluating agricultural land use (Herzog *et al.* 2006; Ruiz-Martinez *et al.* 2015).

| Production systems | C-IT | C-IT | C-NT | C-NT | O-IT | O-IT | O-RT | O-RT |
|---|---|---|---|---|---|---|---|---|
| Cover cropping | Control | CC | Control | CC | Control | CC | Control | CC |
| **Energy use (liter fuel ha-1 year-1) *** | | | | | | | | |
| sowing (cover crops) | | 3.8 | | 3.8 | | 3.8 | | 3.8 |
| mulching (cover crops) | | 3.5 | | | | 3.5 | | 3.5 |
| primary tillage (plough) | 26.1 | 26.1 | | | 26.1 | 26.1 | | |
| seedbed (rotary harrow) | 11.5 | 11.5 | | | 11.5 | 11.5 | | |
| shallow tillage (rotary harrow, disc harrow) | | | | | | | 14.8 | 14.8 |
| glyphosate | | | 1.8 | 1.8 | | | | |
| sowing (main crops) | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 |
| fertilizer applications | 10.6 | 10.6 | 10.6 | 10.6 | | | | |
| slurry applications | | | | | 0.4 | 0.4 | 0.4 | 0.4 |
| herbizide applications | 1.8 | 1.8 | 1.8 | 1.8 | | | | |
| mechanical weed control | | | | | 5.5 | 5.5 | 5.5 | 5.5 |
| total | 53.8 | 61.1 | 17.9 | 21.7 | 47.4 | 54.7 | 24.6 | 31.9 |
| relative scaling § | **0.9** | **1.0** | **0.3** | **0.4** | **0.8** | **0.9** | **0.4** | **0.5** |
| **N supply (kg N ha$^{-1}$ year$^{-1}$) **** | 100 | 100 | 100 | 100 | 69 | 69 | 69 | 69 |
| relative scaling § | **1.0** | **1.0** | **1.0** | **1.0** | **0.7** | **0.7** | **0.7** | **0.7** |
| **Pesticide (kg ha$^{-1}$ active substance) ***** | | | | | | | | |
| Glyphosate | | | 2.88 | 2.88 | | | | |
| Isoproturon | 1.20 | 1.20 | 1.20 | 1.20 | | | | |
| Diflufenican | 0.06 | 0.06 | 0.06 | 0.06 | | | | |
| Ioxynil | 0.30 | 0.30 | 0.30 | 0.30 | | | | |
| Sulcotrione | 0.30 | 0.30 | 0.30 | 0.30 | | | | |
| Terbuthylazine | 0.80 | 0.80 | 0.80 | 0.80 | | | | |
| Nicosulfuron | 0.04 | 0.04 | 0.04 | 0.04 | | | | |
| total | 2.7 | 2.7 | 5.6 | 5.6 | | | | |
| relative scaling § | **0.5** | **0.5** | **1.0** | **1.0** | **0.0** | **0.0** | **0.0** | **0.0** |
| **Averaged intensity score** | **2.4** | **2.5** | **2.3** | **2.4** | **1.5** | **1.6** | **1.1** | **1.2** |

* Energy use measured as l fuel per ha and year . Includes primary tillage, seedbed preparation, sowing, fertilization spraying, and mechanical weed control. Sowing (all systems) and mulching (except C-NT) were included as additional management operations for the cover crop treatments.

** Supply of plant available N in the organic systems is calculated as: a * $NH_4$-$N_{slurry}$ + b * ($Ntot_{slurry}$ - $NH_4$-$N_{slurry}$). a: $NH_4$-N volatilization coefficient during application (0.8), b: percent of organic N mineralized (0.35) (Vitousek *et al.*, 1997; Burney *et al.*, 2010; Geiger *et al.*, 2010; Tsiafouli *et al.*, 2015). It is assumed that all mineral-N supplied to the conventional system is available to plants.

*** Pesticide measured as kg applied active substances per ha.

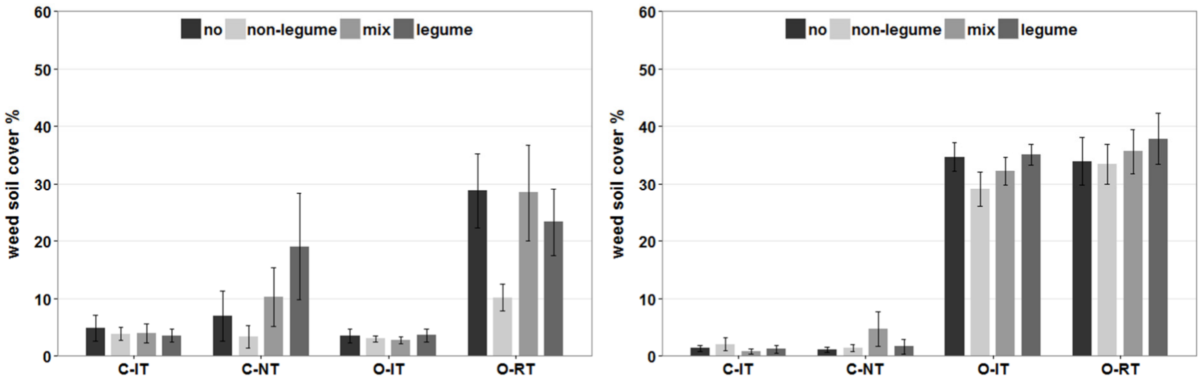
§ Relative scaling of the input factors among the production systems was calculated relative to the highest value (=1), for the corresponding impact factor.

**Supplementary Table S3 I** Grain yield, N content and N concentration of wheat and maize in different production systems and with different cover crop treatments (mean ± s.e.m.). (C-IT: conventional intensive tillage, C-NT: conventional no tillage, O-IT: organic intensive tillage, O-RT: organic reduced tillage). Different letters indicate significant differences among main factor levels (P. system and cover crop) and among cover crop within each production system (Tukey-Test, α = 0.05). ANOVA output ($F_{(df1,df2)}$ values) is also displayed for each variable (*p<0.05, **p<0.01, ***p<0.001).

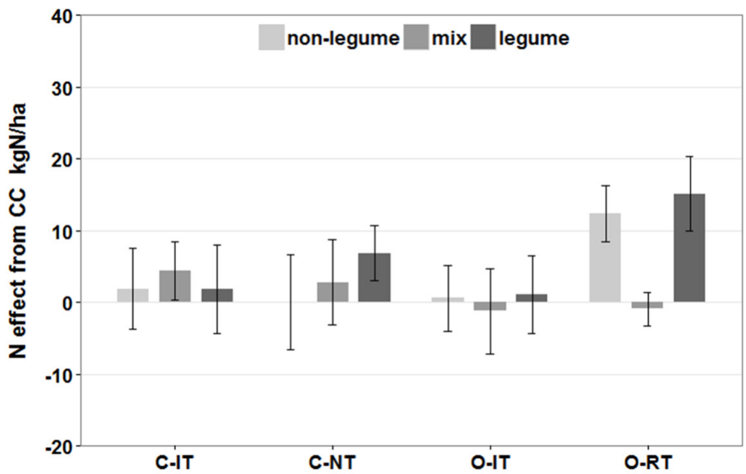
| P. system | cover crop | grain yield (t ha$^{-1}$) | | | | grain N uptake (kg ha$^{-1}$) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Winter wheat | | Maize | | Winter wheat | | Maize | |
| C-IT | | 4.3 ± 0.09 | a | 9.8 ± 0.15 | a | 107 ± 2.7 | a | 172 ± 4.3 | a |
| C-NT | | 4.5 ± 0.09 | a | 8.6 ± 0.20 | b | 108 ± 2.5 | a | 144 ± 5.6 | b |
| O-IT | | 3.2 ± 0.11 | b | 6.7 ± 0.29 | c | 67 ± 4.1 | b | 102 ± 6.1 | c |
| O-RT | | 2.7 ± 0.11 | b | 4.9 ± 0.32 | d | 56 ± 2.8 | b | 73 ± 6.2 | d |
| | no | 3.5 ± 0.17 | a | 6.8 ± 0.46 | a | 82 ± 5.4 | a | 108 ± 9.1 | a |
| | non-legume | 3.7 ± 0.14 | ab | 6.8 ± 0.43 | a | 85 ± 4.8 | a | 108 ± 8.7 | a |
| | legume | 3.8 ± 0.16 | b | 8.3 ± 0.37 | b | 88 ± 4.8 | a | 140 ± 8.0 | b |
| | mixture | 3.6 ± 0.18 | ab | 8.1 ± 0.35 | b | 83 ± 5.6 | a | 136 ± 7.6 | b |
| C-IT | no | 4.3 ± 0.10 | a | 9.6 ± 0.33 | a | 105 ± 5.4 | a | 165 ± 8.7 | ab |
| | non-legume | 4.2 ± 0.21 | a | 9.4 ± 0.23 | a | 107 ± 5.7 | a | 160 ± 8.2 | b |
| | legume | 4.3 ± 0.23 | a | 10.3 ± 0.30 | a | 107 ± 5.8 | a | 184 ± 7.8 | a |
| | mixture | 4.3 ± 0.15 | a | 10.0 ± 0.30 | a | 109 ± 5.9 | a | 178 ± 7.8 | ab |
| C-NT | no | 4.3 ± 0.20 | a | 8.0 ± 0.34 | a | 106 ± 4.9 | a | 130 ± 10.7 | a |
| | non-legume | 4.4 ± 0.13 | a | 8.2 ± 0.50 | ab | 106 ± 5.5 | a | 132 ± 14.0 | a |
| | legume | 4.6 ± 0.22 | a | 9.3 ± 0.31 | b | 112 ± 4.4 | a | 162 ± 7.6 | b |
| | mixture | 4.4 ± 0.19 | a | 9.0 ± 0.33 | ab | 108 ± 5.3 | a | 153 ± 9.0 | b |
| O-IT | no | 3.1 ± 0.24 | a | 5.7 ± 0.63 | a | 67 ± 10.6 | a | 82 ± 11.4 | a |
| | non-legume | 3.2 ± 0.18 | a | 5.4 ± 0.46 | a | 68 ± 8.3 | a | 78 ± 9.8 | a |
| | legume | 3.6 ± 0.20 | a | 7.4 ± 0.28 | b | 68 ± 6.8 | a | 119 ± 9.4 | b |
| | mixture | 3.1 ± 0.25 | a | 8.1 ± 0.27 | b | 66 ± 8.3 | a | 129 ± 8.4 | b |
| O-RT | no | 2.4 ± 0.14 | a | 3.8 ± 0.59 | a | 49 ± 3.8 | a | 55 ± 10.7 | a |
| | non-legume | 3.0 ± 0.19 | b | 4.2 ± 0.49 | a | 62 ± 5.6 | bc | 61 ± 9.5 | a |
| | legume | 3.0 ± 0.24 | b | 6.0 ± 0.71 | b | 65 ± 6.5 | c | 95 ± 14.7 | b |
| | mixture | 2.4 ± 0.22 | a | 5.5 ± 0.51 | b | 49 ± 4.9 | ab | 82 ± 10.3 | b |
| ANOVA | | | | | | | | | |
| Experiment (E) | | $2.0_{(6,21)}$ | ns | $29.3_{(1,21)}$ | *** | $26.1_{(1,21)}$ | *** | $113.5_{(1,21)}$ | *** |
| Block (E:B) | | $1.6_{(6,21)}$ | ns | $0.6_{(6,21)}$ | ns | $4.1_{(6,21)}$ | ** | $1.3_{(6,21)}$ | ns |
| P. system (PS) | | $33.0_{(3,21)}$ | *** | $75.3_{(3,21)}$ | *** | $59.4_{(3,21)}$ | *** | $120.0_{(3,21)}$ | *** |
| cover crop (CC) | | $3.6_{(3,84)}$ | * | $30.7_{(3,84)}$ | *** | $2.4_{(3,84)}$ | ns | $43.2_{(3,84)}$ | *** |
| PS x CC | | $1.6_{(9,84)}$ | ns | $2.7_{(9,84)}$ | ** | $1.4_{(9,84)}$ | ns | $2.1_{(9,84)}$ | * |

**Supplementary Table S3** I continued.

| P. system | cover crop | grain N concentration (g kg$^{-1}$ DM) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Winter wheat | | | | Maize | | | |
| C-IT | | 25.1 | ± | 0.6 | a | 17.4 | ± | 0.2 | a |
| C-NT | | 24.5 | ± | 0.6 | a | 16.5 | ± | 0.3 | b |
| O-IT | | 21.0 | ± | 0.7 | b | 15.1 | ± | 0.4 | c |
| O-RT | | 20.8 | ± | 0.6 | b | 14.5 | ± | 0.4 | c |
| | no | 22.9 | ± | 0.7 | a | 15.3 | ± | 0.4 | a |
| | non-legume | 22.8 | ± | 0.7 | a | 15.3 | ± | 0.4 | a |
| | legume | 23.0 | ± | 0.7 | a | 16.6 | ± | 0.3 | b |
| | mixture | 22.7 | ± | 0.8 | a | 16.3 | ± | 0.3 | b |
| C-IT | no | 24.6 | ± | 1.2 | a | 17.1 | ± | 0.5 | ab |
| | non-legume | 25.5 | ± | 1.4 | a | 17.0 | ± | 0.5 | a |
| | legume | 25.0 | ± | 1.2 | a | 17.8 | ± | 0.4 | b |
| | mixture | 25.2 | ± | 1.3 | a | 17.7 | ± | 0.4 | b |
| C-NT | no | 24.8 | ± | 1.3 | a | 16.1 | ± | 0.7 | a |
| | non-legume | 23.9 | ± | 1.5 | a | 15.7 | ± | 0.8 | a |
| | legume | 24.7 | ± | 1.0 | a | 17.4 | ± | 0.5 | b |
| | mixture | 24.6 | ± | 1.4 | a | 17.0 | ± | 0.5 | b |
| O-IT | no | 21.1 | ± | 1.8 | a | 14.1 | ± | 0.6 | a |
| | non-legume | 21.2 | ± | 1.6 | a | 14.3 | ± | 0.7 | a |
| | legume | 21.0 | ± | 1.4 | a | 16.0 | ± | 0.8 | b |
| | mixture | 20.8 | ± | 1.5 | a | 15.9 | ± | 0.7 | b |
| O-RT | no | 21.1 | ± | 1.3 | a | 13.8 | ± | 0.8 | a |
| | non-legume | 20.5 | ± | 1.1 | b | 14.1 | ± | 0.8 | a |
| | legume | 21.2 | ± | 1.2 | b | 15.4 | ± | 0.7 | b |
| | mixture | 20.3 | ± | 1.4 | a | 14.8 | ± | 0.6 | b |
| ANOVA | | | | | | | | | |
| Experiment (E) | | $299.6_{(6,21)}$ | *** | | | $318.8_{(1,21)}$ | *** | | |
| Block (E:B) | | $4.0_{(6,21)}$ | ** | | | $2.2_{(6,21)}$ | ° | | |
| P. system (PS) | | $37.4_{(3,21)}$ | *** | | | $60.9_{(3,21)}$ | *** | | |
| cover crop (CC) | | $0.2_{(3,84)}$ | ns | | | $53.1_{(3,84)}$ | *** | | |
| PS x CC | | $0.8_{(9,84)}$ | ns | | | $2.1_{(9,84)}$ | * | | |



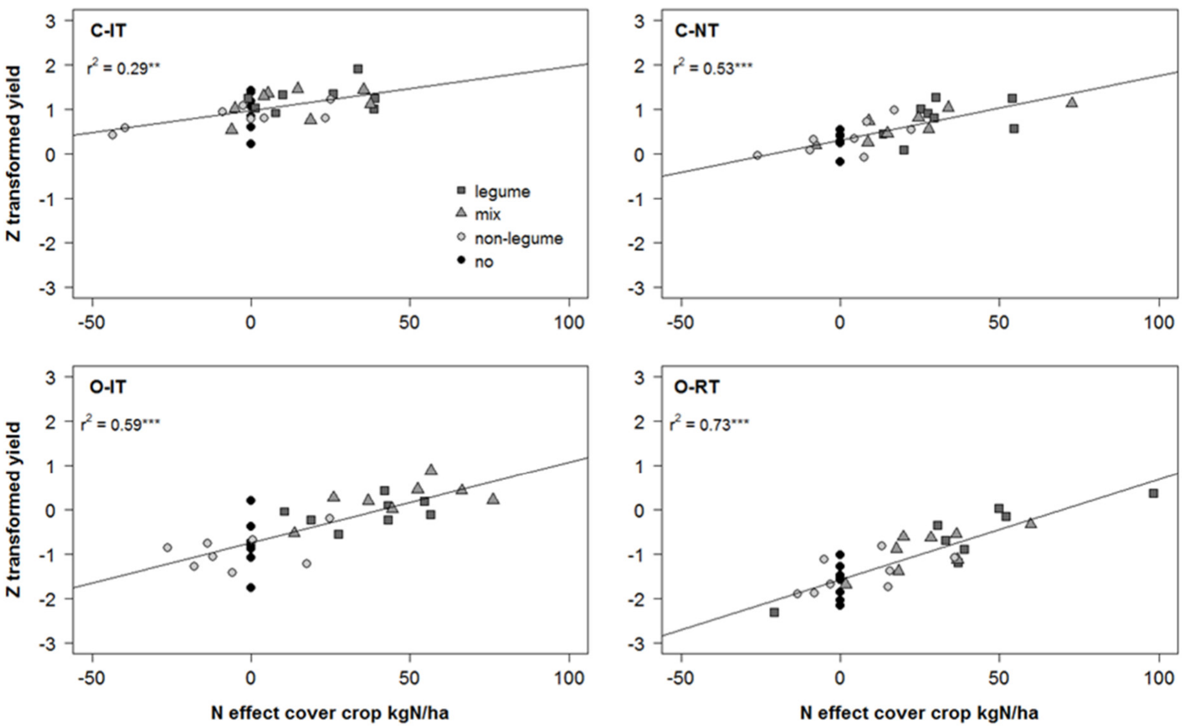

**Supplementary Figure S2 I** Weed soil cover (%) (mean ± s.e.m., n=8) in wheat at tillering (top) or maize at 8 leaf stage (bottom) for the different production systems (C-PT: conventional intensive tillage, C-NT: conventional no tillage, O-PT: organic intensive tillage, O-RT: organic reduced tillage) in combination with cover crop treatment.



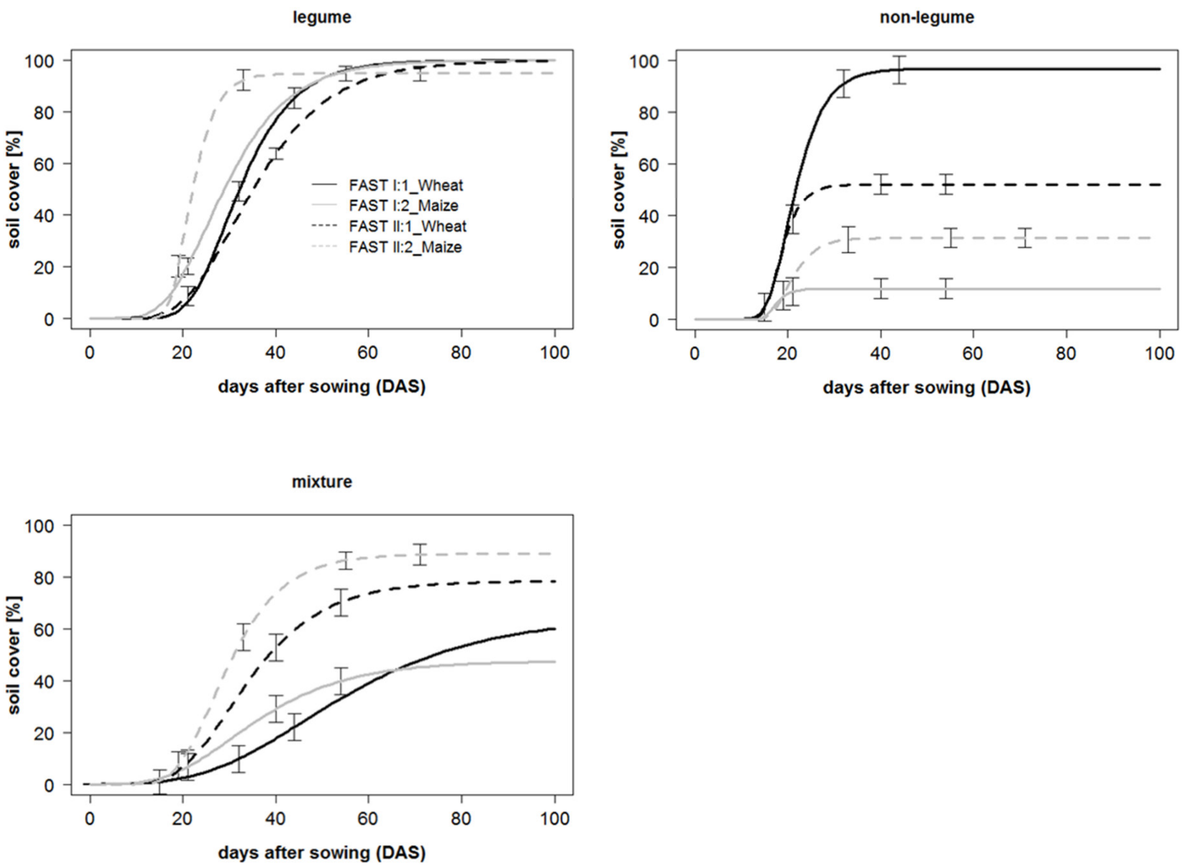

**Supplementary Figure S3 I** N effect from cover crop on N uptake (NeffCC = Nupt CC - Nupt Control) of wheat (mean ± s.e.m., n=8). (C-IT: conventional intensive tillage, C-NT: conventional no tillage, O-IT: organic intensive tillage, O-RT: organic reduced tillage).

**Supplementary Table S4 I** Cover crop N content (N total), the fraction of N derived from biological nitrogen fixation (% Ndfa), the amount of N derived from biological N fixation (Ndfa) and the additional amount of N taking up by maize due to the presence of the legume cover crop (NeffCC). Data for the legume cover crop (hairy vetch) before maize are shown (mean ± s.e.m.). (C-IT: conventional intensive tillage, C-NT: conventional no tillage, O-IT: organic intensive tillage, O-RT: organic reduced tillage).

| system | Ntot kg/ha | | | | %Ndfa | | | | Ndfa kg/ha | | | | NeffCC [kg/ha] | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C-IT | 117 | ± | 13 | a | 89 | ± | 1.2 | a | 104 | ± | 11 | a | 19 | ± | 6 | a |
| C-NT | 99 | ± | 9 | a | 91 | ± | 0.8 | a | 90 | ± | 8 | a | 32 | ± | 5 | ab |
| O-IT | 111 | ± | 11 | a | 88 | ± | 1.0 | a | 98 | ± | 10 | a | 37 | ± | 6 | ab |
| O-RT | 93 | ± | 6 | a | 89 | ± | 1.5 | a | 83 | ± | 6 | a | 40 | ± | 12 | b |




**Supplementary Figure S4 I** Correlations between N effect from cover crop and the standardized (z-transformed) yield of maize for each of the four productions systems. Yield values for maize were standardized across both experiments (FAST I and FAST II) to evaluate the effects of cover crop independently from yield differences among experiments. The N effect of the cover crop was calculated according to equation (1). R-squared for each system is displayed with individual significance levels (**p<0.01, ***p<0.001)




**Supplementary Figure S5 I** Cover crop growth curves for the legume (common vetch and hairy vetch), non-legume (white mustard) and the cover crop mixtures in each trial (FAST I, FAST II) for wheat and maize. Curves are fitted with the Gompertz growth function of the R-package drc (Ritz C. and Streibig, 2005). The model-based standard errors used for the error bars are calculated as the fitted value plus/minus the estimated error, times the 97.5% quantile in the t distribution with degrees of freedom equal to the residual degrees of freedom for the model.

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# CHAPTER 3

## Cover crops as a tool to reduce reliance on intensive tillage and nitrogen fertilization in conventional arable cropping systems

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**Abstract**

Cover crops are often recommended as a valuable practice to develop more sustainable cropping systems but, despite many benefits, their adoption in practice is still limited mainly because the effects on productivity and economic return are variable. Furthermore, it is still unclear under which combinations with other management practices (e.g. tillage, fertilization, weed control) cover crops can provide the highest paybacks.

Here we tested whether cover crops are a suitable management tool to reduce fertilizer input, tillage intensity and herbicide use in Swiss arable cropping systems. We compared the effects of four different cover crop treatments (fallow, radish, subterranean clover and hairy vetch) on maize at two fertilization levels combined with three levels of tillage intensity. To unravel the effects of cover crops on maize growth, we assessed vegetation dynamics using the Normalized Differential Vegetation Index (NDVI) from aerial spectral imagery.

Cover crops on average increased yields by 12% (+7% to +20%) and cover crop effects depended on tillage intensity, fertilization level and cover crop treatment for most of the assessed maize parameters. Best results were obtained with hairy vetch, which increased maize N uptake by 79 kg ha$^{-1}$ on average. As a consequence, at least combinations of two of the three targeted inputs (tillage, fertilization and herbicides) could be successfully reduced, e.g. tillage and fertilization under no tillage or tillage and herbicides under reduced tillage. Even under intensive tillage, both legume cover crops allowed a reduction of fertilization without compromising yield. Spectral imagery analysis showed that legume cover crops compensated for delayed N availability in reduced and no tillage systems and cover crops contributed to enhanced N uptake and crop growth later in the season.

We provide evidence that cover crop based cropping systems can be used to reduce synthetic inputs and tillage without compromising yield, thus presenting an example of ecological engineering. We highlight the importance of considering the whole set of management practices when adopting cover cropping in order to maintain or increase productivity with reduced anthropogenic inputs under conventional cropping.

**Highlights**

- Nitrogen fertilization can be reduced after legume cover crops without compromising yield.
- Tillage intensity can be reduced only in combination with cover cropping.
- Weed control under reduced tillage is challenging, even with cover crops.
- Maize depleted nitrogen in absence of a legume cover crop.
- Aerial spectral imagery provided insight into crop growth dynamics.

**Keywords:** conservation agriculture; drone imagery; ecological intensification; maize; hairy vetch

## Introduction

The intensification of arable production have made a substantial contribution to increased world food production over the last 50 years (Tilman *et al.*, 2002). However, current agricultural practices have also given rise to environmental concerns regarding decreased biodiversity, reduced water quality, and degraded soil quality (Stoate *et al.*, 2001). Although the use of mineral fertilizers and pesticides has led to a considerable increase in productivity, arguably the main ecosystem service provided by agriculture, this has been at the cost of other regulating and supporting services provided by agro-ecosystems (Power, 2010). The internal regulation of nutrient cycles, the natural control of pests and diseases, and the abundance and diversity of soil organisms are often downregulated in intensively managed fields. As a result, high agricultural productivity becomes dependent on anthropogenic-synthetic inputs and is no longer sustainable in the long-term (Geiger *et al.*, 2010; Tsiafouli *et al.*, 2015).

Ideally, a sustainable system will maintain the right balance between external inputs and ecosystem service delivery, thus providing high productivity based on optimized internal regulatory processes and resilience of the system (Bender *et al.*, 2016). This goal could be achieved by including agricultural practices that promote regulating and supporting ecosystem services and preserving soil quality, also called ecological engineering.

One example of this is conservation agriculture (CA), which principles include reduced tillage, improved crop rotation, and permanent soil coverage (Teasdale *et al.*, 2007; Hobbs *et al.*, 2008; Doltra and Olesen, 2013). Although CA contributes to soil conservation, reduced consumption of fossil fuels, a reduced work load, and is widely propagated in the America's and Australia, adoption rates in Europe are still very low (Derpsch *et al.*, 2010; Kertész and Madarász, 2014; Casagrande *et al.*, 2016). The main reasons why CA is not widely adopted in Europe include the often more complex crop rotations (e.g. presence of ley), problems related to weed control, and delayed spring nutrient mineralization.

Another option to improve the sustainability of agricultural production is the use of cover crops. Cover crops are grown between two main crops and are a crucial element of CA systems to reach an appropriate soil coverage during fallow period as well as maintain productivity (Hartwig and Ammon, 2002; Pittelkow *et al.*, 2015; Marcillo and Miguez, 2017). Cover crops provide a range of ecosystem services, as they have been shown to protect soil against erosion, reduce the risk of surface and ground water pollution, improve soil structure, and promote soil biota (Dabney *et al.*, 2001; Kohl *et al.*, 2014; Schipanski *et al.*, 2014; Blanco-Canqui *et al.*, 2015). Moreover, cover crops play an important role in the management of nitrogen (N) within arable cropping systems, either by preventing leaching losses (non-legume species) (De Notaris *et al.*, 2018; Thapa *et al.*, 2018) or by providing additional N input through biological fixation (legume species) (Thorup-Kristensen *et al.*, 2003; Couëdel *et al.*, 2018). Cereal-based systems, particularly maize, benefit greatly from additional N input by legume cover crops, as shown by several studies (Miguez and Bollero, 2005; Gabriel and Quemada, 2011; Liebman *et al.*, 2012; Tosti *et al.*, 2012; Komainda *et al.*, 2017).

All these benefits have been extensively described as well as the importance of direct cover crop management, e.g. sowing and termination date or termination techniques (Thorup-Kristensen and Dresboll, 2010; Alonso-Ayuso *et al.*, 2014; Radicetti *et al.*, 2016; Osipitan *et al.*, 2019). Cover crops have also been shown to be important when conservation tillage is applied or to reduce N applications. However, few studies have investigated to which extent cover crop based agro-ecosystem services are influenced by the combination of these management practices or, more generally, perform within defined cropping systems. (Wittwer *et al.*, 2017). Both tillage and fertilization greatly influence soil properties and processes, such as organic matter mineralization (Balesdent *et al.*, 1990; Kandeler *et al.*, 1999) and weed abundance, which in turn influence crop nutrition and productivity (Shelton *et al.*, 2017). For example, it is still unclear if and to which extent cover crops can reduce the reliance on fertilizers under different tillage intensities without impairing crop yield. Moreover, earlier studies reported that legume cover crops can fix more than 100 kg N $ha^{-1}$ $year^{-1}$, but it is still difficult to predict how much of this N can be effectively used by the following crop (Thorup-Kristensen *et al.*, 2003; Büchi *et al.*, 2015). Additionally, cover crops could suppress weeds and thus have the potential to reduce tillage and herbicide use, especially if cover crops can be easily managed before the main crop is planted (Dorn *et al.*, 2015). Thus, it is increasingly important to gain a clearer understanding of the interactions between cover cropping and other field management practices, such as tillage intensity or fertilization in an effort to optimize cover crop effects on productivity and profitability, and thereby achieve a wider adoption of this practice by farmers as a mean of ecological intensification (Roesch-McNally *et al.*, 2017).

Consequently, this study focuses on the interactions between tillage intensity, N fertilization and cover cropping in Swiss conventional arable crop production. Two replicated field experiments were conducted during the years 2012-2014 and 2013-2015 with a crop sequence of winter wheat, cover crops, and maize in Eastern Switzerland. The effect of three different cover crops (hairy vetch (*Vicia villosa*), oilseed radish (*Raphanus sativus*) and subterranean clover (*Trifolium subterraneum*)) were compared to fallow combined with three levels of tillage intensity coupled with weed control strategy (intensive tillage with herbicides, reduced tillage without herbicides, and no tillage with herbicides) and two levels of N fertilization.

The main aim of the study was to evaluate the extent to which the use of cover crops can decrease dependency on intensive tillage, synthetic N fertilization, and herbicides. Thus, based on the assumptions that:

i) cover crops help to reduce tillage intensity,
ii) additional N input provided by legume cover crops can partly replace the addition of synthetic N fertilizer, and
iii) the combination of cover cropping and reduced tillage allows a reduced use of herbicides,

we aimed to identify best combinations of the investigated management practices to sustain productivity but reduce anthropogenic inputs.

## Materials and methods

### *Study site and field experiments*

Two field experiments were conducted during the years 2012-14 (Experiment I) and 2013-15 (Experiment II) at the research station Agroscope in Tänikon, Switzerland (47°28'50'' N, 8°54'25'' E, 537 m a.s.l.). The top soil of both experiments is classified as sandy loam, containing on average 21% clay, 35% silt and 44% sand, with 2.1 % organic carbon content, 0.23 % total nitrogen content, and it had a pH ($H_2O$) of 7. The long-term (1981-2010) mean annual temperature is 8.7°C, while annual precipitation averages 1184 mm. Weather conditions in the experimental years did not substantially deviate from the long-term averages (2014: 10°C and 1113 mm, 2015: 9.8°C and 927 mm). However, a slight drought period occurred from July to September 2015 (Supplementary Figure S1).

The two experiments have exactly the same experimental design and the only difference is the start date, where experiment II starts one year later. This was done to obtain a more robust understanding of the treatment effects across years. The two experiments (I and II) were arranged in a strip-split-plot design with four replicates. Factor I (main plots, only applied to maize) was three levels of tillage intensity coupled with weed management strategy: 1) intensive tillage (IT) by mouldboard ploughing and use of post-emergence herbicides, 2) no-tillage (NT) with the use of glyphosate and post-emergence herbicides, and 3) reduced tillage (RT) by shallow non-inversion tillage and mechanical weed control in maize. Factor II (subplot CC) consisted of four different cover crop treatments: 1) oilseed radish (cv. Pegletta) as a fast growing non-legume cover crop (RS), 2) hairy vetch (cv. Hungvillosa) as a high biomass overwintering legume cover crop (VV), 3) subterranean clover (cv. Campeda) as a self-re-seeding specie, which was already undersown in the previous crop (winter wheat) as living mulch and should also act as cover crop before maize (TS), and 4) fallow (as control). Although, the aim was that subterranean clover can re-establish by itself, it was re-sown after winter wheat harvest because the re-seeding rate was too low for appropriate soil coverage. Factor III (subplot F) was ammonium nitrate application to the main crops either at the norm (normN) or half rate (halfN) of what is recommended to farmers in Switzerland (Flisch *et al.*, 2009). The combination of these three factors resulted in 24 treatment-combinations and 96 plots per experiment. The size of the main plot (tillage) was 384 $m^2$ (12x32m) and the smallest plot size was 48 $m^2$ (6x8m) (Figure 1).

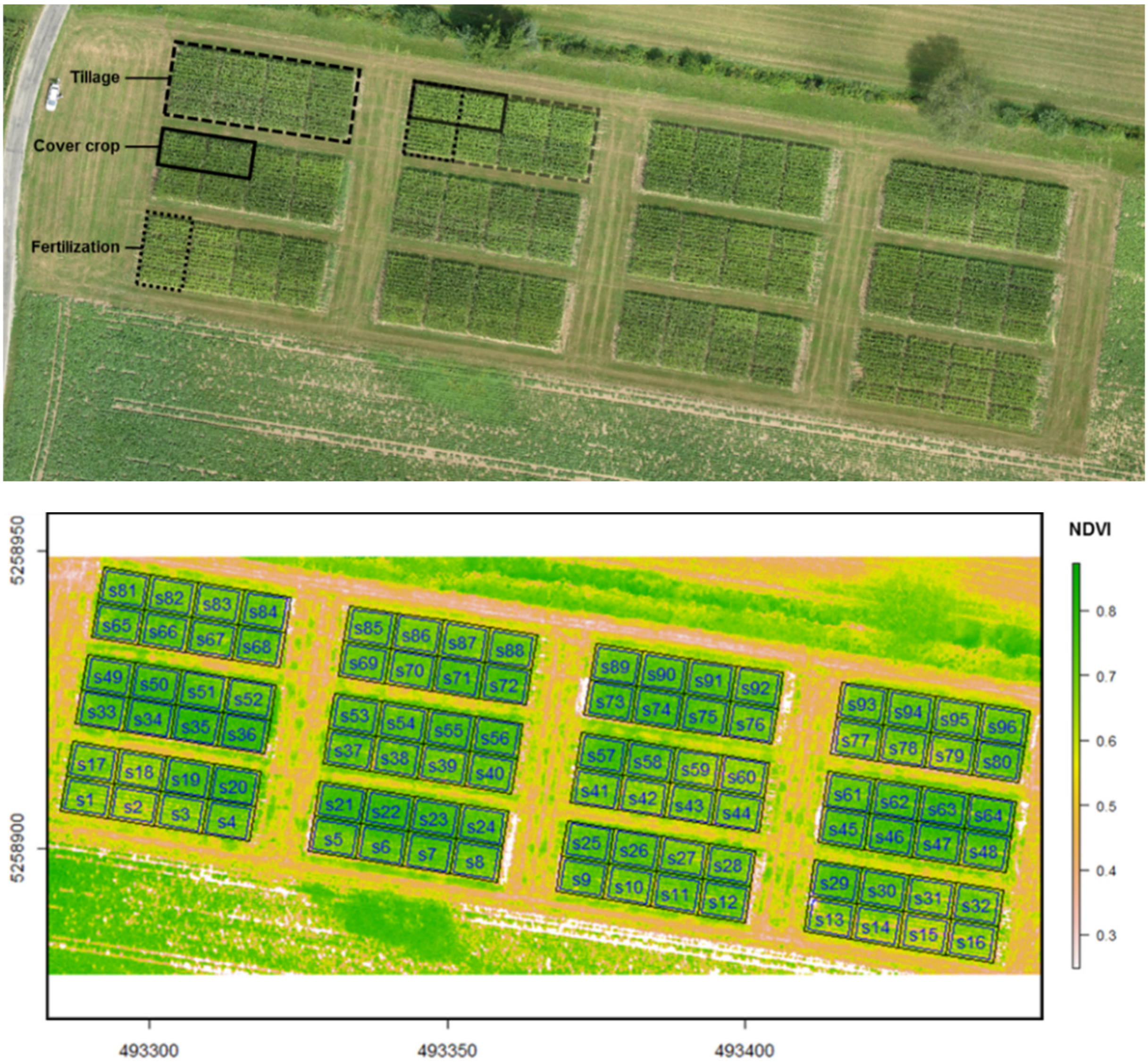


**Fig. 1 Top Aerial picture of experiment II (10.08.2015) computed from drone imagery** (eBee AG, SenseFly) with the software Postflight Terra 3D (Pix4D). Arrangement of main plots (tillage) and the crossed-split-plots (cover crop and fertilization) are drawn to illustrate the experimental design. Bottom NDVI index map (10.08.2015) created with the software PostflightTerra 3D (Pix4D, version 4.0.104), which was used to monitor maize growth.

***Crop management***

The two experiments consisted of a winter wheat - cover crop - maize crop sequence. In the years preceding the experiments, the fields were managed conventionally and annually ploughed 20-25 cm deep. Forage pea (*Pisum sativum* subsp. *arvense*) was grown prior to the start of the experiments, and, after ploughing the experimental field, winter wheat (*Triticum aestivum* L. cv. 'CH Claro') was sown early October (5.20.12 in Exp. I and 3.10.13 in Exp. II) either as pure crop (control, RS and VV cover crop treatments) or intercropped with subterranean clover (TS treatment). Weed control in wheat was performed by herbicide application in the pure wheat plots (control, RS and VV cover crop treatments), whereas no weed control was performed in the intercropped wheat (TS treatment). The normN fertilization plots received a total of 140 kg N ha$^{-1}$ in three applications (70/30/40), and the halfN fertilization plots a total of 70 kg N ha$^{-1}$ in two applications (45/25). The results from the wheat-clover intercropping treatment have already been published (Radicetti *et al.*, 2018), and in this study we focus on the effect of cover cropping, coupled with tillage and fertilization, on maize production.

After wheat harvest (3.8.13 in Exp. I and 25.7.14 in Exp. II), the straw was removed from the plots and all three winter cover crops (RS, VV, and TS) were sown (21.8.13 in Exp. I and 7.8.14 in Exp. II) after a shallow stubble cultivation (rotary cultivator at 5cm soil depth, also in the control plots). Cover crops and weeds in control plots were terminated the next spring by either tillage (IT and RT treatments, 18.5.14 in Exp. I and 13.5.15 in Exp. II) or by applying 1.44 kg ha$^{-1}$ (active ingredient) glyphosate in the NT treatment (30.4.14 in Exp. I and 29.4.15 in Exp. II). The IT treatment consisted of mouldboard ploughing at 20cm soil depth and a seed bed preparation with a rotary harrow at 5cm soil depth. The RT treatment was performed with a precision cultivator (Weco-dyn, Friedrich Wenz GmbH) in three passes: the first two passes at 2-3 cm and the third one at 5-6 cm soil depth. Cover crop biomass was mulched with a flail mower prior to tillage operations in the IT and RT treatments.

Maize (*Zea mays* L. cv. ' LG 30.222') was sown at the end of May (22.5.14 in Exp. I and 28.5.15 in Exp. II) with a row distance of 0.75 m and combined with an underfoot starter-fertilization of 30 kg N ha$^{-1}$ in both fertilization treatments. The normN plots received an additional 60 kg N ha$^{-1}$ (90 kg N in total) and the halfN plots additional 15 kg N ha$^{-1}$ (45 kg N in total) at maize growth stage BBCH15-17. Weeds during maize growth were controlled by herbicides in the IT and NT treatments, but were controlled mechanically by hoeing two times in the RT treatment. Primary tillage and post-emergence weed control were combined in one factor as they are both integrated part of weeding strategies. Indeed, herbicides are commonly applied in conventional systems and glyphosate application is still predominating in no tillage systems. The use of reduced tillage without herbicides was therefore designed in one hand to reduce tillage intensity and to avoid the use of glyphosate as well as post-emergence herbicides. Thus, the two factor-combinations RT/TS/50N and RT/TS/100N did not receive any herbicide during the experimental period and the other RT treatments no herbicides in maize only. Maize was harvested as whole plant (9.10.14 in Exp. I and 8.10.15 in Exp. II) and as grain (30.10.14 in Exp. I and 28.10.15 in Exp. II). Additional information regarding field operations (dates, amount applied, and machinery) can be found in supplementary Table S1.

***Measurements***

Cover crop growth was monitored by evaluating the percentage of soil covered by cover crop species and weeds at 20, 30 and 60 days after sowing (DAS). Two pictures per plot were taken at 180cm height, covering 1 $m^2$ ground surface, using a bipod stand. Total plant soil cover was then determined with the program ASSESS 2.0 (Lamari, 2008) based on colour saturation. The percentage of soil covered by cover crops versus weeds was then determined visually based on the pictures. Additionally, cover crop and weed biomass were determined before termination in spring by cutting the plants 1 cm above the soil surface within two randomly placed quadrants (50cm x 50cm) per subplot. Weed and cover crop species were sorted for each sample before dry weight determination.

In maize, weed density and biomass were assessed at the end of maize flowering (BBCH69) to determine weed pressure in four quadrants (50cm x 50cm) per subplot. Mean values – for cover, density, and biomass data – were calculated for each subplot and used for the analyses.

Maize biomass (whole plant) and grain yield were determined by harvesting two rows in each plot (7 m length) with adapted plot-sized combine harvesters. Biomass and grain weights were directly measured by the harvesters and a subsample was collected per plot for dry matter and nutrient content determination. Dry matter content was determined by oven-drying plant material (cover crops, weeds, maize biomass and grain) at 105°C for 30 hours to adjust yield and biomass data to t dry matter (DM) $ha^{-1}$. Plant materials for nutrient analyses were oven-dried at 60°C and finely ground. The N and C concentrations of cover crop biomass as well as N concentration of maize biomass and grain were then determined using elemental analysis by the Dumas method (Dumas, 1831).

To assess the impact of the treatment combinations on the N status of the different cropping systems, we calculated the overall N balance as the difference between the total amount of N input and the amount of N exported at harvest. Here, N input is the combination between the N applied as mineral fertilizer (Nfert) and an estimation of N fixed by the legume cover crops (Nfix). Nfix was calculated as the N content in cover crops at termination multiplied by the percentage of N derived from the atmosphere (%Ndfa) using values obtained by Büchi et al. (2015) for subterranean clover and hairy vetch in Switzerland. A positive N balance reflects an N surplus in the system and a negative balance implies that soil N was depleted.

Additionally, the N Nutrition Index (NNI) was computed for each plot as the ratio between measured maize biomass N concentration and the critical N concentration (Ncrit.) calculated after Plénet and Lemaire (1999):

$$Ncrit. = 3.40 * (biomass)^{-0.37} \quad (1)$$

In order to assess the contribution of cover crops to maize N nutrition, a cover crop N effect (NeffCC) was calculated (Tosti *et al.*, 2012):

$$NeffCC,i = NuptCC,i - NuptCtr \quad (2)$$

where NuptCC,i is the N uptake of the main crop after a cover crop treatment and NuptCtr is the N uptake of the main crop after the control treatment without cover crops. NeffCC values were calculated separately for the normN and halfN treatments. Additionally, the effect of N fertilization was calculated for the control plots by subtracting the N uptake of the halfN to the N uptake of the normN control plots for each tillage treatments.

Maize growth over the whole vegetation period was additionally monitored in experiment II (2015) with the help of the Normalized Differential Vegetation Index (NDVI) obtained from unmanned aerial vehicle (UAV) imagery. NDVI is a well-recognized vegetation index (Tucker, 1979) that gives information about the status of a crop and is calculated based on the red and near-infrared (NIR) reflectance values of a crop canopy as follow:

$$NDVI = (NIR - red) / (NIR + red) \quad (3)$$

The experimental field was regularly monitored with a NIR modified camera (Canon S110 NIR, 12 MP), mounted on an automated fixed-wings UAV (eBee AG, senseFly), acquiring image data in the near-infrared (850nm), red (625nm), and green (550nm) spectral band at an average ground resolution of 2cm per pixel. NDVI values at the plot level were then obtained for each flight by extracting the mean pixel value from NDVI index-maps created with the software PostflightTerra 3D (Pix4D, version 4.0.104) (Figure 1). Reflectance values for each pixels were calibrated with the camera settings by the software but no further radiometric calibration were performed. However, all flights were conducted under sunny conditions (without clouds) between 12pm and 2pm to reduce the impact of varying light conditions (Rasmussen *et al.*, 2016). Maize growth curves were then obtained for each plot by fitting data with the loess function (span=0.5) (Cleveland and Devlin, 1988) and the following physiological parameters were then extracted for growth dynamics analyses (Fig. 2):

- MaxNDVI: the maximal NDVI value across the vegetation period
- Time integrated NDVI (TIN): daily (interpolated) integration of NDVI for the entire duration of the vegetation period, also split at 76 DAS (half of the maize vegetation period) into the growth period (TINgrowth) and the senescence period (TINsen)
- Growth rate (GRate): mean daily growth rate until 76 DAS (half of the maize vegetation period).

***Statistical analysis***

Statistical analyses were all performed using R (R Core Team, 2020). Variance analyses on the assessed variables were performed using a strip-split-plot design with “tillage” (IT, NT, RT) as the main plot, and “cover crop” (control, RS, TS, VV) and “fertilization” (normN, halfN) as crossed-subplot in an ANOVA using linear mixed effects models (Kuznetsova *et al.*, 2015). The terms “experiment” and “replicate blocks within experiment” were included first in the model to account for their variation. Tillage, cover crop, and fertilization as well as their interactions were considered as fixed effects. Additionally, and because the experiments (I and II) were performed in two years (2014 and 2015), the interactions of experiment (year) and the three main factors were also included in the model. To identify suitable combination of cover crops with tillage and fertilization, all treatments were additionally contrasted against the reference treatment with intensive tillage, norm fertilization and no cover crop using the R package lsmeans (Lenth, 2018). Contrasts were also used to test if the N balances differ from 0 (neutral N balance).Data were square root transformed when residual plots revealed deviation from normality: that is for N content and C/N ratio of cover crops, weed biomass in cover crops and both weed density measures in maize. For a better interpretation of the results, these data were back-transformed in the figures and tables.

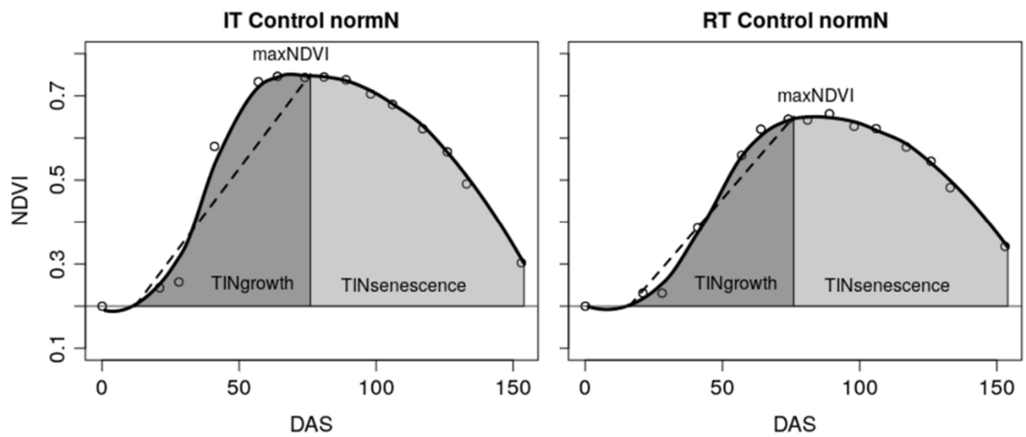


**Fig. 2 Maize growth curves (solid black) fitted over NDVI measurements (circles) for two plots in 2015 and the calculated phenological indexes;** maxNDVI, Time Integrated NDVI (TIN, divided in TINgrowth and TINsenescence) and Growth Rate (dashed line) (see section 2.3 in the Materials and methods for detailled index descriptions).

**Table 1: Statistical ANOVA output demonstrating the effects of the main factors experiment (year), tillage, cover crop and fertilisation and their interaction terms on the assessed variables in maize.** $F_{(df1,df2)}$ values (df1: numerator degrees of freedom; df2: denominator degrees of freedom) and significance level (ns: non-significant; * $p<0.05$; ** $p<0.01$; *** $p<0.001$). NNI = Nitrogen Nutrition Index; NeffCC = N effect from cover crops; max NDVI = maximal NDVI value across the growing season; Time integrated NDVI (TIN): daily (interpolated) integration of NDVI for the entire duration of the vegetation period; Growth rate (GRate): mean daily growth rate until half growing season (76 days after sowing).

| | Factors | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Variables | Exp | Exp:Block | Tillage (T) | Cover crop (CC) | Fertilization (F) | T x CC | CC x F | T x F | T x CC x F | Year x T | Year x CC | Year x F |
| | | | | | | | Cover crop | | | | | |
| Weed cover 60 DAS | ns | ns | ns | $210.4_{(3,60)}^{***}$ | ns | ns | $4.3_{(3,63)}^{**}$ | ns | ns | ns | $7.0_{(3,60)}^{***}$ | ns |
| Weed biomass spring | $11.3_{(1,12)}^{**}$ | ns | ns | $143.5_{(3,60)}^{***}$ | $6.8_{(1,20)}^{*}$ | ns | $4.5_{(3,63)}^{**}$ | ns | ns | ns | $19.8_{(3,60)}^{***}$ | ns |
| Cover crop cover 60 DAS | $6.8_{(1,12)}^{*}$ | ns | ns | $29.4_{(3,40)}^{***}$ | $8.3_{(1,20)}^{**}$ | ns | $11.1_{(2,42)}^{***}$ | $6.8_{(2,20)}^{**}$ | ns | ns | $10.1_{(2,40)}^{***}$ | $8.0_{(1,20)}^{*}$ |
| Cover crop biomass spring | ns | ns | ns | $139.6_{(2,40)}^{***}$ | $4.9_{(1,20)}^{*}$ | ns | ns | ns | ns | ns | ns | ns |
| Cover crop N content | ns | ns | ns | $236.6_{(2,40)}^{***}$ | ns | ns | ns | ns | ns | ns | ns | ns |
| Cover crop C/N ratio | ns | ns | ns | $293.6_{(2,40)}^{***}$ | ns | ns | $4.8_{(2,42)}^{*}$ | ns | ns | ns | $24.8_{(2,40)}^{***}$ | ns |
| Cover crop Ndfa | ns | ns | ns | $239.0_{(2,20)}^{***}$ | ns | ns | ns | ns | ns | ns | ns | ns |
| | | | | | | | Maize | | | | | |
| Weed density after weed control | ns | ns | $6.9_{(2,12)}^{*}$ | ns | ns | ns | ns | ns | ns | ns | ns | ns |
| Weed biomass after weed control | ns | ns | $28.4_{(2,12)}^{***}$ | ns | ns | ns | ns | ns | ns | $15.9_{(2,12)}^{***}$ | ns | ns |
| Biomass | $25.5_{(1,12)}^{***}$ | ns | $17.7_{(2,12)}^{***}$ | $50.0_{(3,60)}^{***}$ | $75.8_{(1,20)}^{***}$ | $8.3_{(6,60)}^{***}$ | $5.7_{(3,63)}^{**}$ | ns | ns | ns | ns | $7.2_{(1,20)}^{*}$ |
| Grain yield | $4.8_{(1,12)}^{*}$ | ns | $10.3_{(2,12)}^{**}$ | $25.9_{(3,60)}^{***}$ | $42.8_{(1,20)}^{***}$ | $3.5_{(6,60)}^{**}$ | $2.9_{(3,63)}^{*}$ | ns | ns | ns | ns | $5.7_{(1,20)}^{*}$ |
| N uptake | $22.1_{(1,12)}^{***}$ | ns | $27.2_{(2,12)}^{***}$ | $131.8_{(3,60)}^{***}$ | $253.4_{(1,20)}^{***}$ | $7.5_{(6,60)}^{***}$ | ns | ns | $2.8_{(6,63)}^{*}$ | ns | ns | $28.3_{(1,20)}^{***}$ |
| NNI | $8.8_{(1,12)}^{*}$ | ns | $39.3_{(2,12)}^{***}$ | $132.7_{(3,60)}^{***}$ | $250.8_{(1,20)}^{***}$ | $3.9_{(6,60)}^{**}$ | ns | ns | ns | ns | ns | $21.3_{(1,20)}^{***}$ |
| NeffCC | $13.5_{(1,12)}^{**}$ | ns | $17.1_{(2,12)}^{***}$ | $95.4_{(2,40)}^{***}$ | ns | $6.9_{(2,40)}^{***}$ | ns | ns | $4.1_{(4,42)}^{**}$ | ns | ns | ns |
| N balance | $5.6_{(1,12)}^{*}$ | ns | $13.1_{(2,12)}^{***}$ | $83.2_{(3,60)}^{***}$ | $79.8_{(1,20)}^{***}$ | ns | ns | ns | $3.0_{(6,63)}^{*}$ | ns | ns | $10.2_{(1,20)}^{***}$ |
| | | | | | | | Maize NDVI (only Experiment II) | | | | | |
| max NDVI | - | ns | $14.9_{(2,6)}^{**}$ | $38.5_{(3,27)}^{***}$ | $42.3_{(1,9)}^{***}$ | $3.5_{(6,27)}^{*}$ | $3.3_{(3,27)}^{*}$ | ns | ns | - | - | - |
| Growth rate (GRate) | - | ns | $13.1_{(2,6)}^{**}$ | $12.9_{(3,27)}^{***}$ | $22.8_{(1,9)}^{**}$ | $3.6_{(6,27)}^{**}$ | $3.7_{(3,27)}^{*}$ | ns | ns | - | - | - |
| Time integrated NDVI (TIN) | - | ns | $16.3_{(2,6)}^{**}$ | $42.1_{(3,27)}^{***}$ | $102.2_{(1,9)}^{***}$ | ns | ns | ns | ns | - | - | - |
| TIN growth | - | ns | $6.8_{(2,6)}^{*}$ | $26.6_{(3,27)}^{***}$ | $37.6_{(1,9)}^{***}$ | ns | ns | ns | ns | - | - | - |
| TIN senescence | - | ns | ns | $22.3_{(3,27)}^{***}$ | $161.5_{(1,9)}^{***}$ | ns | ns | ns | ns | - | - | - |

## Results

### *Cover crop performance*

All three cover crops established satisfactorily, with over 65 % soil cover 60 days after sowing and significantly suppressed weeds compared to the control treatment (Table 1, Supplementary Table S2). Hairy vetch produced the highest biomass, with on average over 3 t $ha^{-1}$ aboveground DM biomass, followed by subterranean clover with over 1 t $ha^{-1}$. Both are overwintering species in contrast to oilseed radish, which was already terminated by frost during winter and left less than 1 t $ha^{-1}$ biomass at termination in spring. Oilseed radish was still able to suppress weeds as well as hairy vetch until spring, whereas subterranean clover was not as efficient (Figure 3). This could be partly due to the slower growth of clover in autumn. The cover crops differed significantly in their N content and C/N ratio. Hairy vetch had the highest aboveground N content (over 140 kg N $ha^{-1}$) and the lowest C/N ratio (10), followed by subterranean clover (32 kg N $ha^{-1}$, C/N ratio of 15) and radish (8 kg N $ha^{-1}$, C/N ratio of 30) (Supplementary Table S2). Overall, cover crop growth did not differ among the main plots and thus left similar conditions before differential tillage was applied to maize. More importantly, the two fertilization levels applied to the previous wheat crop had only minor effects on cover crop performance with overall a significant but slightly higher cover crop biomass after half fertilization in wheat (+ 0.12 t $ha^{-1}$). This was mainly driven by a higher biomass for the legume cover crops under half fertilization (note that fertilization was applied to wheat but not directly applied to the cover crops). However, absolute differences were marginal.

The amount of aboveground atmospheric fixed N added by the legume cover crops was estimated at 125 kg N $ha^{-1}$ for hairy vetch and 19 kg N $ha^{-1}$ for subterranean clover (Supplementary Table S2). This large difference was due to the differences in biomass production and differences in the %Ndfa estimation factor, which was 88% for vetch and 61% for subterranean clover.

### *Weed pressure*

Although weeds were successfully controlled during the cover cropping period, cover crops generally had little impact on weed pressure in maize. The largest and most significant differences were observed on weed biomass at maize flowering between the different tillage and weed control strategies (Table 1, Figure 3). In the reduced tillage treatment, with only mechanical weed control, weeds could not be fully controlled. In contrast weed biomass was very low in the intensive tillage treatment and in the NT treatment, where glyphosate was applied, in combination with post-emergence herbicides to control weeds.

Although no herbicides were applied in the TS treatment in the previous crop (wheat) and TS did not suppressed weeds as well as RS and VV during the cover crop period, this did not result in higher weed pressure in maize compared to the other cover crop treatments (Figure 3). N fertilization had no impact on weed pressure in maize and is therefore not displayed in Figure 3.

***Maize productivity***

All three treatment factors (e.g. fertilization, tillage and cover crop) significantly influenced maize biomass and grain yield (Table 1). The highest maize grain yield was obtained after intensive tillage (9.8 t DM $ha^{-1}$ averaged across the treatments), and it was slightly but not significantly lower under no tillage (-10 %, 8.9 t DM $ha^{-1}$), and significantly lower after reduced tillage without herbicide (-22 %, 7.6 t DM $ha^{-1}$). Averaged across treatments, the norm N fertilization rate increased grain yield by 0.75 t DM $ha^{-1}$ compared to half fertilization. Lastly, all three cover crop treatments significantly increased grain yield compared to fallow (8.0 t DM $ha^{-1}$). The yield gain after cover crops was moderate after oilseed radish (+7 %, 8.5 t DM $ha^{-1}$) and subterranean clover (+11 %, 8.9 t DM $ha^{-1}$), and highest after hairy vetch (+ 20%, 9.6 t DM $ha^{-1}$).

Interestingly, significant interactions between cover crop and tillage, as well as cover crop and fertilization were observed (Table 1) indicating that the effect of the cover crops on maize yield depended on tillage treatment and fertilization treatment. For instance, consistent positive effects of all cover crops were observed under no tillage compared to the fallow treatment (RS: +12%, TS: +14%, VV: +19%), whereas only the two legume cover crop treatments increased yield under IT (TS: +9% and VV: +10%) and only hairy vetch significantly increased yield under RT (VV: +36%). Moreover, no significant yield differences were observed between half and norm fertilization within the legume cover crops (TS and VV), whereas significantly less yield was obtained with half fertilization after fallow (-10%) or radish (-13%). Finally, all treatment were contrasted against the reference system with intensive tillage, norm fertilization and no cover crop. Several cover crop combinations with no tillage and reduced tillage and with half fertilization under no tillage were not significantly different (Figure 4). This indicate that inputs (e.g. fertilization or energy for tillage) could be successfully reduced but yield level was maintained.

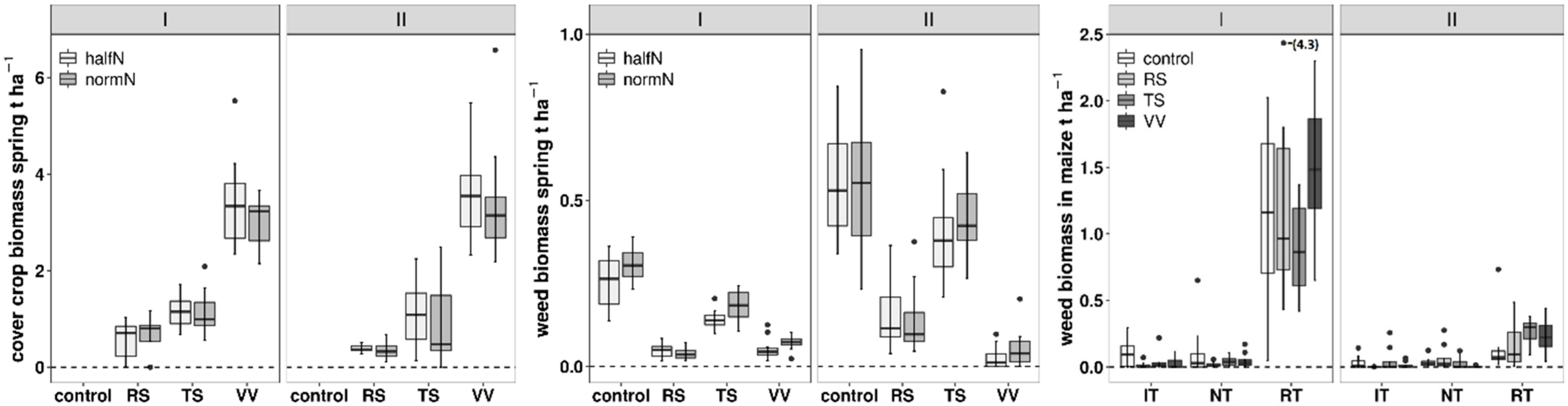


**Figure 3: Cover crop biomass and weed biomass at cover crop termination (spring) and weed biomass in the maize crop at flowering.** The factor tillage (only applied to maize) is not significant for the cover crop data and fertilization is not significant in maize and are therefore not presented. (IT: intensive tillage, NT: no tillage, RT: reduced tillage) (control: no cover crop, RS: oilseed radish, TS: sub. clover, VV: hairy vetch).

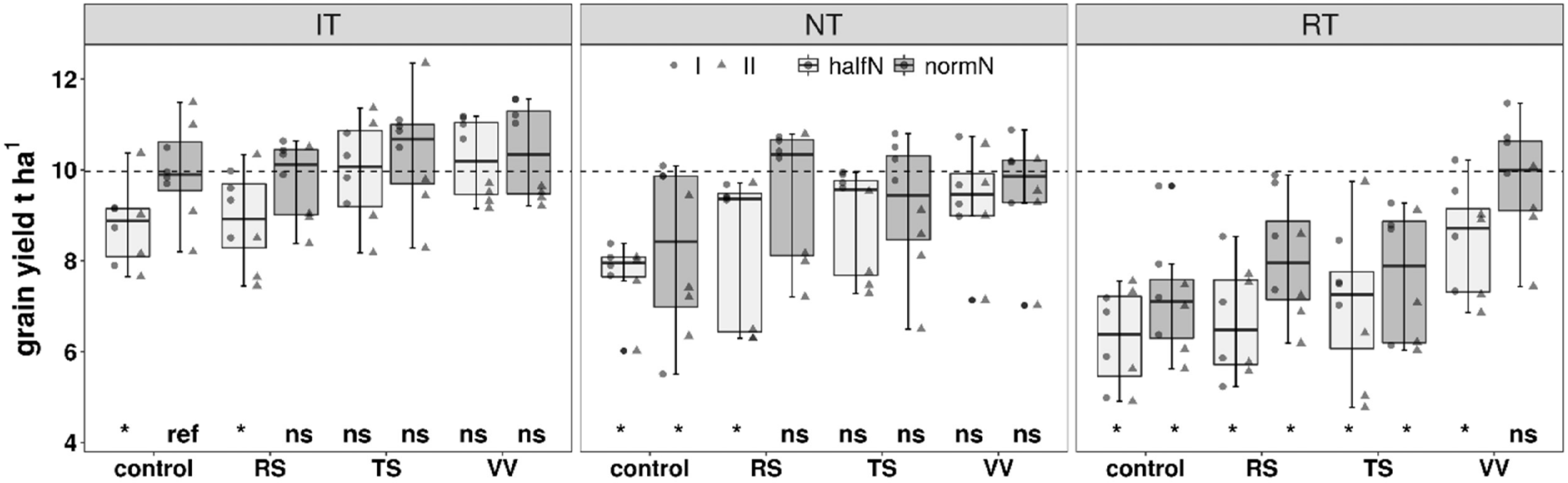


**Figure 4: Maize grain yield for the main factor combinations.** The circles and triangles are the individual values for experiment I and II. The dashed line shows the mean yield level in the reference treatment with intensive tillage, no cover crop and norm fertilisation (ref). * indicate significant difference (<0.05) compared to the ref treatment, ns not significantly different from ref (contrast with adjusted p-value after Benjamini and Hochberg). (IT: intensive tillage, NT: no tillage, RT: reduced tillage) (control: no cover crop, RS: oilseed radish, TS: sub. clover, VV: hairy vetch) (normN: norm fertilization, halfN: half fertilization).

Overall, yield level corresponded to mean yield expectation for Switzerland (10 t ha$^{-1}$) but was higher in Exp. I (2014) than in Exp. II (2015). The reduced yield in 2015 could be partly explained by the lower precipitation amount in July and August 2015 (Supplementary Figure S1), which could have negatively influenced N availability. The interaction of year with fertilization also points in this direction (Supplementary Figure S2). However, tillage and cover crop effects did not vary between Exp. I and Exp. II as revealed by the absence of a significant interaction term between year and tillage or year and cover crop treatment.

### *Maize nutrition and growth*

Similar to the yield results, the N uptake of maize was significantly influenced by tillage, cover crop and fertilization as well as the interaction between cover crop and tillage (Table 1, 2). The highest N uptake was observed under intensive tillage (194 kg ha$^{-1}$ ± 12 ci), was not significantly lower under no tillage (182 kg ha$^{-1}$ ± 11 ci) but significantly lower under reduced tillage (145 kg ha$^{-1}$ ± 12 ci). Across all tillage and cover crop treatments, norm fertilization increased N uptake by 32 kg ha$^{-1}$. All cover crops also significantly increased maize N uptake compared to fallow (142 kg ha$^{-1}$ ± 10 ci) and differed from each other with increasing effect from radish to hairy vetch (RS: 157 kg ha$^{-1}$ ± 11 ci, TS: 175 kg ha$^{-1}$ ± 14 ci, VV: 221 kg ha$^{-1}$ ± 12 ci).

In order to assess the contribution of cover crops to maize N uptake, a cover crop N effect (NeffCC) was calculated (see equation (2) in the methods). NeffCC was significantly different among tillage and cover crop treatments but not among fertilization treatments (Table 1, 2). Averaged across all tillage systems and compared to bare fallow, radish increased N uptake by 15 kg ha$^{-1}$, subterranean clover by 33 kg ha$^{-1}$ and vetch by 79 kg ha$^{-1}$. In comparison, adding 45 kg N as mineral fertilizer increased maize N uptake by 40 kg ha$^{-1}$ in the control plots without cover crops, regardless of tillage intensity. However, the overall cover crop effect was highest under intensive tillage (57 kg ha$^{-1}$ ± 10 ci) and significantly lower under no and reduced tillage (NT: 37 kg ha$^{-1}$ ± 7 ci, RT: 33 kg ha$^{-1}$ ± 11 ci).

The N Nutrition Index (NNI) for maize also revealed the importance of increased N uptake, as only the treatments which attained an N uptake of about 215 kg N ha$^{-1}$ reached an NNI of 1 indicating no N limitation (Supplementary Figure S3). This was the case for almost all hairy vetch plots (except under RT 50N) and maize following subterranean clover but with full fertilization (except under RT) (Table 2).

**Table 2: Maize total N uptake and N effect from cover crops (NeffCC) (mean ± ci, n = 8) for half and norm fertilisation.** NeffCC values under half fertilization were calculated in relation to the halfN control plots for each tillage system (light grey), and values under norm fertilization were calculated in relation to the normN control plots (dark grey). (IT: intensive tillage, NT: no tillage, RT: reduced tillage) (control: no cover crop, RS: oilseed radish, TS: sub. clover, VV: hairy vetch).

| Tillage | Cover crop | **N uptake (kg N ha$^{-1}$)** | **NeffCC (kg N ha$^{-1}$)** | **N uptake (kg N ha$^{-1}$)** | **NeffCC (kg N ha$^{-1}$)** |
|---|---|---|---|---|---|
| | | halfN | halfN | normN | normN |
| IT | Control | 131 ± 16 | | 171 ± 17 | 40 ± 8 |
| | Oilseed radish (RS) | 165 ± 17 | 33 ± 20 | 191 ± 18 | 20 ± 6 |
| | Subclover (TS) | 176 ± 25 | 43 ± 29 | 215 ± 23 | 44 ± 7 |
| | Hairy vetch (VV) | 241 ± 20 | 109 ± 27 | 262 ± 13 | 91 ± 8 |
| NT | Control | 133 ± 19 | | 176 ± 27 | 42 ± 7 |
| | Oilseed radish (RS) | 141 ± 21 | 7 ± 7 | 184 ± 33 | 9 ± 5 |
| | Subclover (TS) | 186 ± 34 | 52 ± 22 | 212 ± 30 | 36 ± 5 |
| | Hairy vetch (VV) | 201 ± 15 | 67 ± 17 | 222 ± 37 | 46 ± 9 |
| RT | Control | 101 ± 21 | | 139 ± 24 | 38 ± 11 |
| | Oilseed radish (RS) | 112 ± 24 | 11 ± 11 | 148 ± 13 | 9 ± 6 |
| | Subclover (TS) | 124 ± 19 | 23 ± 12 | 134 ± 12 | -5 ± 8 |
| | Hairy vetch (VV) | 176 ± 19 | 76 ± 8 | 223 ± 16 | 84 ± 10 |

To better understand the temporal dynamics behind treatment effects, maize growth was monitored during the growing season in experiment II in 2015 based on NDVI from UAV imagery (Figure 5). The tillage effect on early crop growth could be detected, as indicated by the phenological parameter growth rate and max NDVI, which were significantly lower under NT and RT than IT. Cover crops, and especially hairy vetch, positively influenced maize growth throughout the growing season. This effect was most pronounced under reduced tillage and intensive tillage early in the season (Figure 5, panel a, b, e, f) when treatments with hairy vetch had enhanced maxNDVI, growth rate and TIN growth levels, more strongly under IT and RT than NT. The positive effect of hairy vetch also appeared under no tillage later on (Figure 5, panel c, d), as higher TINsen values were obtained under no tillage and the factor tillage was not anymore significant (Table 1, Supplementary Figure S4).

### *N balance*

When assessing the impact of cover crops on overall N fluxes, we found that the effects were similar among the tillage and fertilization treatments, with a positive N balance after hairy vetch (+ 42 ± 14 ci) and negative values for the other cover crop treatments (Control: -35 ± 14 ci, RS: -47 ± 8 ci, TS: -36 ± 11 ci) indicating that in those treatments maize removed more N from the soil compared to what was added. The higher N input from hairy vetch led to neutral N balance under half fertilization (except under RT) and a significantly positive N balance under norm N fertilization. In general, more neutral N balances were obtained under RT, mostly with full fertilization, in contrast to either negative or positive N balances under IT and NT (Figure 6).

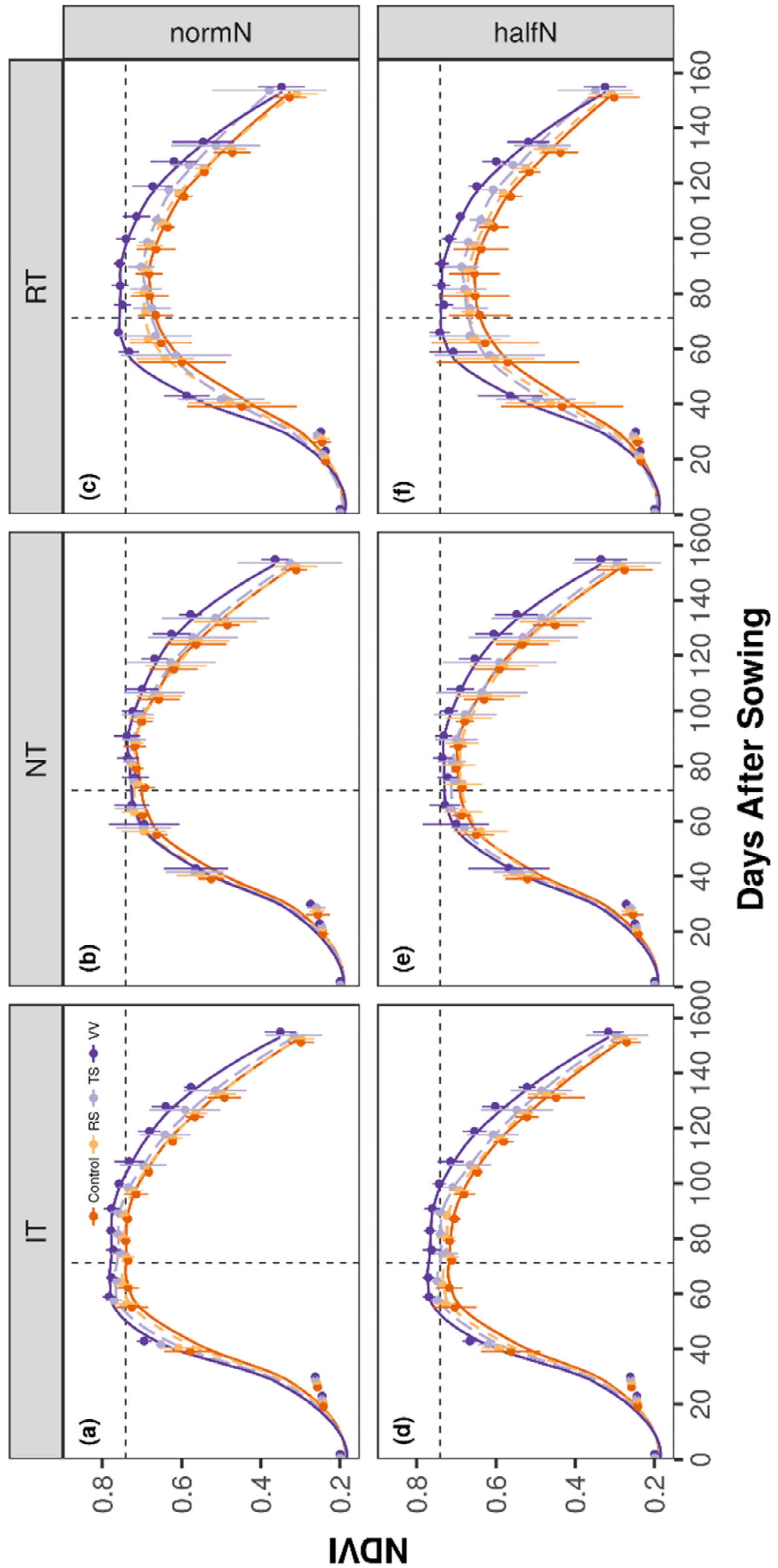


**Figure 5: Maize growth curves** (NDVI over growing season, mean ± ci, n = 4) with four cover crop treatments (red = control; green = oilseed radish (RS); blue = sub. clover (TS); violet = hairy vetch (VV)) under intensive tillage (IT), no tillage (NT) and reduced tillage (RT) and norm and half fertilization. To ease interpretation, the two dashed lines indicate the maximum NDVI value and the day at which it was reached for the reference treatment intensive tillage, no cover crop and norm fertilization (reference treatment).

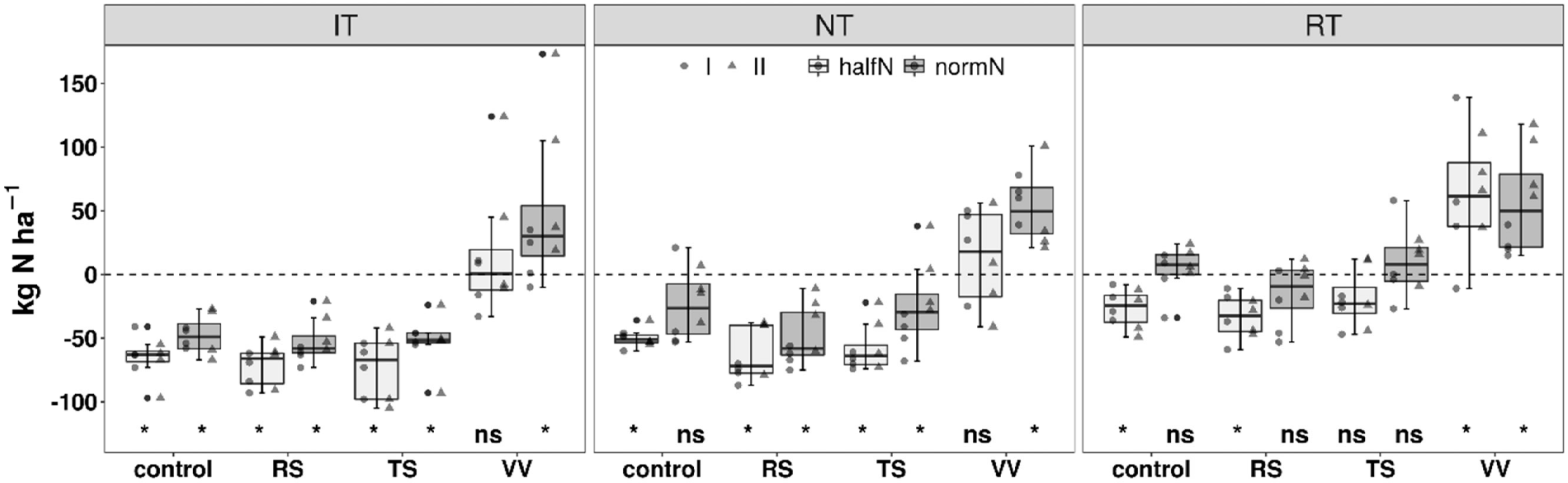


**Figure 6: Nitrogen balance of maize for all treatment combinations calculated as N input (Nfert + Nfix) minus N exported by the grains.** Positive values indicate that not all added nitrogen was removed at harvest while negative values indicate that more N was removed compared to what was added with fertilisation and biological N fixation in legumes. The circles and triangles are the individual values for experiment I and II. * indicate values significantly different from 0, ns mean no significant differences (contrast with adjusted p-value after Benjamini and Hochberg) (IT: intensive tillage, NT: no tillage, RT: reduced tillage) (control: no cover crop, RS: oilseed radish, TS: sub. clover, VV: hairy vetch) (normN: norm fertilization, halfN: half fertilization).

**Discussion**

It is known that cover crops can contribute to more sustainable cropping systems (Olesen *et al.*, 2007; Schipanski *et al.*, 2014; Giuliano *et al.*, 2016). Although positive effects of cover crops on crop yield have been widely described (Tonitto *et al.*, 2006; Marcillo and Miguez, 2017) there is still poor adoption by farmers at a larger scale (Panagos *et al.*, 2015; Seifert *et al.*, 2018), even if various national and regional incentives have recently initiated a positive trend and higher integration of cover crops into rotations (Storr *et al.*, 2019). Still, one key aspect to increase the use of cover crops would be to improve the return on invest for farmers by optimizing cover crop based systems in order to increase profitability. This can be achieved either by reducing synthetic inputs (e.g. fertilizers, pesticides) and energy use (e.g. fuel for tillage) or by significantly increasing yield, also called ecological intensification. Moreover, for farmers it is important to know under which conditions and with which field operations cover crops are most beneficial to fulfill these expectations.

In our study, we focused on conventional cereal based cropping systems, which are one of the most widespread agricultural production systems in Europe or North America (FAO, 2019). Cereal-based systems are characterized by high inputs of fertilizers and pesticides, and, at least in Europe, relatively high tillage intensity. Finding ecological cropping practices that can substitute a certain amount of inputs while maintaining productivity, also called ecological engineering, is therefore needed to design more sustainable cropping systems (Bender *et al.*, 2016). We were particularly interested in understanding to which extent other field practices influence cover crop effects, and therefore finding most promising combinations of cover cropping with tillage intensity, N fertilization and weed control strategy.

Our results underline earlier findings that introducing cover crops allows a reduction of tillage intensity (Mirsky *et al.*, 2012; Wittwer *et al.*, 2017; Büchi *et al.*, 2018), as similar yield could be achieved under no and reduced tillage compared to our reference treatment with intensive tillage, full fertilization and no cover crop. We also found that legume cover crops can deliver substantial amounts of N to the following crop, achieving similar yields even when N fertilization was halved (Marcillo and Miguez, 2017). The addition of hairy vetch, a high biomass legume cover crop, enhanced maize N uptake substantially (e.g. up to 109 kg N $ha^{-1}$ additional uptake). Such effects were already observed in other studies (Tosti *et al.*, 2012) but it was still not well known that such results also apply for systems with reduced or no tillage where mineralization rate are expected to be lower and residues left at the surface. Moreover, the obtained results were consistent across different years, showing that these results were repeatable and were not much influenced by inter-annual climatic variations at our experimental site. Note that precipitations are not a main limiting factor in this region and that outcome could be different in water limited regions.

Our results also indicate that N input by legume cover crops more positively impacted N balance than mineral fertilization as neutral balances were achieved with hairy vetch under half fertilization in contrast to full fertilization but no cover crop. Interestingly, the N balance for maize was only positive in treatments after hairy vetch as a cover crop, while in all other treatments the N balance was negative, indicating that maize removed more nitrogen from the soil compared to what was added. However, it is also important to note that a positive N balance can also indicate a higher risk of N leaching, because N surplus and, in case of mineralisation, enhanced soil N availability could potentially be lost if not synchronized with crop needs. On the other hand, one advantage of legume derived N is that it is generally less prone to leaching than mineral N, as organic N is better retained in the soil (Crews and Peoples, 2005; Tosti *et al.*, 2019). Thus even if an important fraction is not recovered in the crop (Almeida Acosta *et al.*, 2011), it has a lower potential to be lost in the environment in contrast to mineral fertilizers (Hansen *et al.*, 2019). Moreover, it was shown that high quality residues of cover crops can support carbon- and nutrient-cycling management through litter feedbacks on decomposition within cropping systems (Barel *et al.*, 2018). Our results demonstrate that reducing N fertilization coupled with a high biomass legume cover crop can achieve a neutral N balance and thus sustain crop growth and N stocks in the system. The higher N balance for the treatment combination with reduced tillage and hairy vetch as cover crop (RT VV) resulted in an N surplus but this could be partly explained through the higher weed biomass in this treatment that probably has taken up a substantial amount of N, which was not accounted in the N balance calculation.

Another important aspect to consider is the interest to reduce the global warming potential of cropping systems (e.g. reduce greenhouse gas emissions). Synthetic fertiliser use is one of the most important factors contributing to the global warming potential in Switzerland and Western Europe (Prechsl *et al.*, 2017) because the production of synthetic nitrogen requires substantial amounts of energy (Woods *et al.*, 2010). Moreover, N fertilization can significantly contribute to greenhouse gas emissions, especially through the production of the greenhouse gas nitrous oxide (Skinner *et al.*, 2019). In contrast, nitrous oxide emissions derived from legume cover crops were shown to be low (Peyrard *et al.*, 2016). Thus, the observation that nitrogen fixing cover crops can maintain yield at the same level, but with 50% less nitrogen input is a promising observation which can help to reduce the contribution of arable cropping systems to global warming.

Earlier studies used drones and UAV imagery to monitor the development of crop yield and the presence of nutrient deficiencies in crops at field scale (Maresma *et al.*, 2016; Rasmussen *et al.*, 2016). So far, UAV imagery has, to our knowledge, not been used to monitor the temporary effects of cover crops or differences between tillage intensities. We used the vegetation index NDVI as a proxy for crop growth and N uptake, which provided new insight behind the temporal dynamic of cover crop effects under different tillage intensities. Overall, tillage mostly influenced early maize growth whereas the use of cover crops before maize had a significant impact throughout the vegetation period. Based on the calculated phenological parameters, legume cover crops could compensate for delayed N availability in reduced and no tillage systems (e.g. Grate, maxNDVI), prolonged N uptake and crop growth later in the season (e.g TIN, TINsen) and also compensated for reduced N fertilization. Based on these phenological parameters, we also found that N availability from legume cover crops is greater when incorporated through tillage (e.g. in the tilled treatments) but also becomes available under no tillage later in the season. Generally, N release from buried plant residues is faster than surface placed residues, and the N concentration and C/N ratio of the initial biomass are determinants for N release kinetic (Justes *et al.*, 2009; Jahanzad *et al.*, 2016). Further research could explore how to adapt fertilization strategies in combination with legume cover crops to best fit crop needs under reduced and no tillage. Finally, all calculated phenological indexes (maxNDVI, Time Integrated NDVI and GrowthRate) significantly correlated with maize biomass and N uptake (Supplementary Figure S4). This also shows the potential of this approach to predict yield and N uptake over larger areas and therefore potentially be used to adapt fertilization depending on crop needs (Maresma *et al.*, 2016; Nuijten *et al.*, 2019).

By combining tillage and weed management we also aimed at reducing herbicide use, particularly under conservation tillage, as the application of herbicides is more and more criticized in society. Our results shows that cover crops did not significantly help to reduce weed pressure in the following maize crop. Although cover crops have the potential to keep weed pressure low, effects are very variable and depend even more on long-term management and initial weed pressure (Osipitan *et al.*, 2019; Reimer *et al.*, 2019). The only treatment with reduced use of herbicides that could maintain yield was the combination of reduced tillage with hairy vetch and norm fertilization. The higher N input by hairy vetch have probably alleviated the competition for nutrients by weeds in this treatment but it remains uncertain if this is a viable practice in the long-term.

In summary, this study demonstrated that best results on productivity were obtained with hairy vetch as a cover crop similarly to Liebman et al. (2018). Moreover, at least combinations of two of the three targeted inputs could be successfully reduced, e.g. tillage and fertilization under no tillage or tillage and herbicides under reduced tillage. Even under intensive tillage, both legume cover crops allowed a reduction of fertilization without compromising yield. However we did not look at long-term effects of having repeated use of legumes as cover crops. Within the same experiment we have found that legume species have the potential to harbor important pest and disease as shown for nematodes (Schmidt *et al.*, 2017) and for *Fusarium* fungi (Walder *et al.*, 2017; Šišić *et al.*, 2018). Thus, their repeated use should be planned with caution. On the other hand, these risks as well as the amount of N delivered by cover crops could be managed by using mixtures of species and make use of their associated multiple services (Amosse *et al.*, 2015; Tribouillois *et al.*, 2015; Finney *et al.*, 2017; Couëdel *et al.*, 2018).

## Conclusions

This study demonstrates that legume cover crops can be used to partly replace fertiliser inputs without compromising yield under intensive and no tillage, and thus confirms that cover cropping has the ability to facilitate conservation agriculture and more extensive cropping practices. Compared to intensive tillage, full fertilisation and herbicide use, similar yields were obtained when either tillage intensity and/or fertilization were reduced in combination with a legume cover crop. Thus, cover crops not only can be used to reduce nutrient leaching and protect soil against erosion, they can also help to reduce fertiliser input and tillage while maintaining typical productivity levels. Cover crops were not able to sufficiently control weeds under reduced tillage and without herbicide but, here again, similar yield could be obtained when N input from fertilization and legume cover crop was sufficient to alleviate negative impact of increased weed pressure.

Overall, this work demonstrates that cover crops are a suitable tool for ecological engineering, but we recommend that farmers and farmer advisors consider the whole set of cropping practices when adopting specific cover crops in order to maintain or increase productivity but reduce inputs needs and costs.

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**Author contributions**

Raphaël A. Wittwer: Conceptualization, Investigation, Formal analysis, Data curation, Writing - original draft, Project administration. Marcel G.A van der Heijden: Conceptualization, Writing - review & editing, Supervision, Funding acquisition.

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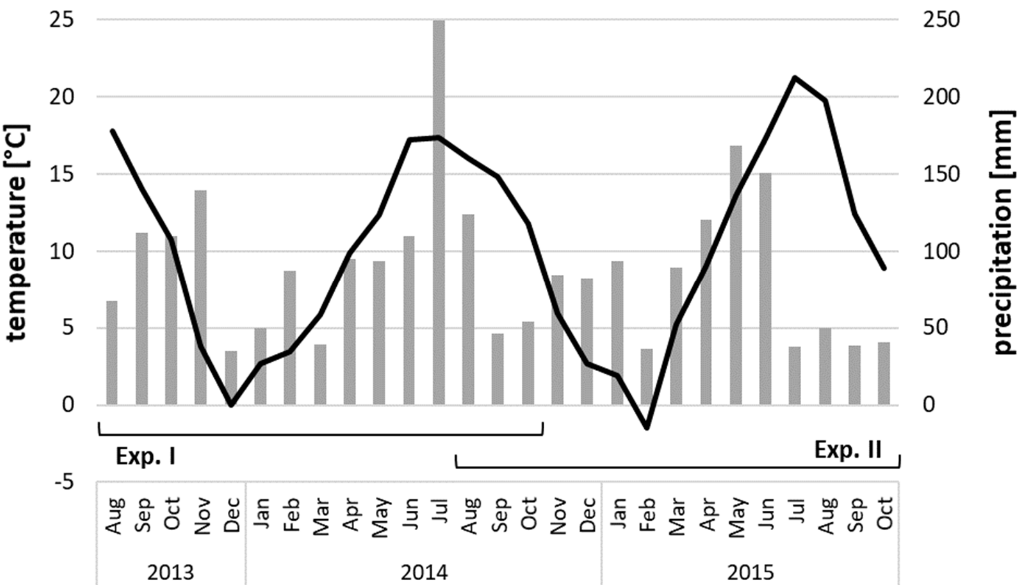
## Supplementary information

**Supplementary Table S1:** Summary of crop management and field operations in experiment 1 (Exp. I) and experiment 2 (Exp. II). IT: intensive tillage, NT: no tillage, RT: reduced tillage / C: no cover crop, RS: oilseed radish, TS: subterranean clover, VV: hairy vetch / 100N: full fertilization, 50N: half fertilization.

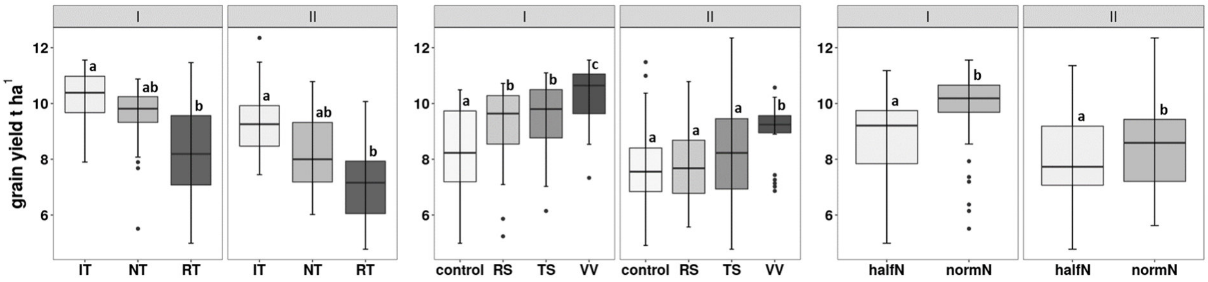
| Field operations | Exp. I | Exp. II | Treatments | Amount / Product / Device |
|---|---|---|---|---|
| **Winter wheat** | | | | |
| Winter wheat sowing<br>Winter wheat + TS sowing | 05.10.2012 | 03.10.2013 | All | **C, RS, VV**: 190 kg ha$^{-1}$<br>**TS**: 170 kg ha$^{-1}$ + 19 kg ha$^{-1}$ TS |
| 1. N fertilization ($NH_4$ - $NO_3$) | 03.04.2013 | 19.03.2014 | All | **100N**: 70 kg N ha$^{-1}$<br>**50N**: 45 kg N ha$^{-1}$ |
| Herbicide application | 25.04.2013 | 04.04.2014 | **all except TS** | 1.1 l Archipel +<br>1.0 l Starrane180 |
| 2. N fertilization ($NH_4$ - $NO_3$) | 25.04.2013 | 17.04.2014 | All | **100N**: 30 kg N ha$^{-1}$<br>**50N**: 25 kg N ha$^{-1}$ |
| 3. N fertilization ($NH_4$ - $NO_3$) | 11.06.2013 | 26.05.2014 | **100N** | **100N**: 40 kg N ha$^{-1}$ |
| Harvest wheat grain | 03.08.2013 | 25.07.2014 | All | |
| Straw removal | 15.08.2013 | 06.08.2014 | All | |
| **Cover crops** | | | | |
| Stubble cultivation (5 cm) | 21.08.2013 | 06.08.2014 | All | Rotary cultivator |
| Cover crop sowing | 21.08.2013 | 07.08.2014 | All | **RS**: 25 kg ha$^{-1}$<br>**TS**: 19 kg ha$^{-1}$<br>**VV**: 100 kg ha$^{-1}$ |
| **Maize** | | | | |
| Glyphosate | 30.04.2014 | 29.04.2015 | **NT** | 4 l Glyphosat 360S |
| Cover crop mulching | 18.05.2014 | 13.05.2015 | **IT, RT** | |
| Moldboard plough (20 cm) | 19.05.2014 | 13.05.2015 | **IT** | |
| Precision cultivator (2-3 cm) | 21.05.2014 | 18.05.2015 | **RT** | Weco-dyn, Wenz GmbH |
| Precision cultivator (5-6 cm) | 21.05.2014 | 28.05.2015 | **RT** | Weco-dyn, Wenz GmbH |
| Seedbed preparation (5 cm) | 21.05.2014 | 28.05.2015 | **IT** | Rotary harrow |
| Maize sowing | 22.05.2014 | 28.05.2015 | All | kg ha$^{-1}$ |
| 1. N fertilization (underfoot) | 22.05.2014 | 28.05.2015 | All | **100N**: 30 kg N ha$^{-1}$<br>**50N**: 30 kg N ha$^{-1}$ |
| Herbicide application | 21.06.2014 | 29.06.2015 | **IT, NT** | Exp.I: 1.5 l Calaris +<br>1.0 l Nicogan +<br>1.2 l Dual Gold<br>Exp.II: 1.5 l Calaris +<br>0.9 l Nicogan +<br>0.2 l Banvel4S |
| 1. hoeing | 23.06.2014 | 29.06.2015 | **RT** | Star cultivator |
| 2. N fertilization ($NH_4$ - $NO_3$) | 03.07 2014 | 30.06.2015 | all | **100N**: 60 kg N ha$^{-1}$<br>**50N**: 15 kg N ha$^{-1}$ |
| 2. hoeing | | 09.07.2015 | **RT** | Star cultivator |
| Harvest biomass | 09.10.2014 | 08.10.2015 | all | |
| Harvest grain | 30.10.2014 | 28.10.2015 | all | |

**Supplementary Table S2:** Weed cover and biomass and Cover crop cover, biomass under the different cover crop treatments. The percentage of cover was assessed at 60 days after sowing (DAS), and the total biomass produced, nutrient content, and nitrogen derived from atmosphere (Ndfa) was measured in the spring directly prior to tillage operations. The values given are the mean ± ci, different letters indicates significant differences between cover crop treatments (Tukey test, p<0.05).

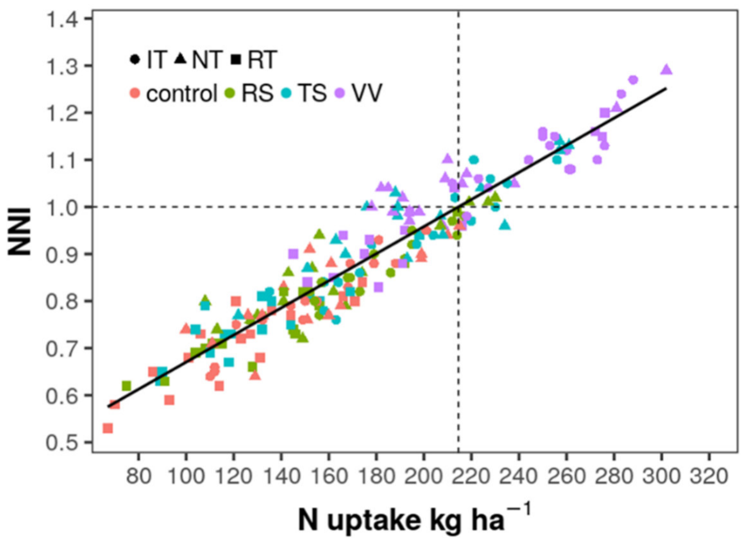
| | **Weed** | | | | **Cover crop** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **cover** | | **biomass** | | **cover** | | **biomass** | | **N content** | | **C/N ratio** | | **Ndfa** | |
| | % at 60 DAS | | [kg ha$^{-1}$] | | % at 60 DAS | | [kg ha$^{-1}$] | | [kg N ha$^{-1}$] | | | | [kg N ha$^{-1}$] | |
| control | 53 ± 3.6 | a | 417 ± 56 | a | - | | - | | - | | - | | - | |
| radish (RS) | 6 ± 1.9 | c | 93 ± 24 | c | 65 ± 5.3 | a | 482 ± 91 | a | 8 ± 1.7 | a | 30 ± 3.0 | a | - | |
| subclover (TS) | 15 ± 3.9 | b | 295 ± 50 | b | 74 ± 6.0 | a | 1075 ± 172 | b | 32 ± 5.4 | b | 15 ± 0.5 | b | 19 ± 3.3 | a |
| hairy vetch (VV) | 4 ± 0.9 | c | 50 ± 12 | c | 96 ± 1.0 | b | 3312 ± 263 | c | 142 ± 11.6 | c | 10 ± 0.2 | c | 125 ± 10 | b |
| F-values, sig. | **163.6**$_{(3,63)}$ | *** | **55.5**$_{(3,63)}$ | *** | **20.5**$_{(2,42)}$ | *** | **140.4**$_{(2,42)}$ | *** | **223.1**$_{(2,42)}$ | *** | **85.4**$_{(2,42)}$ | *** | **394.3**$_{(1,21)}$ | *** |



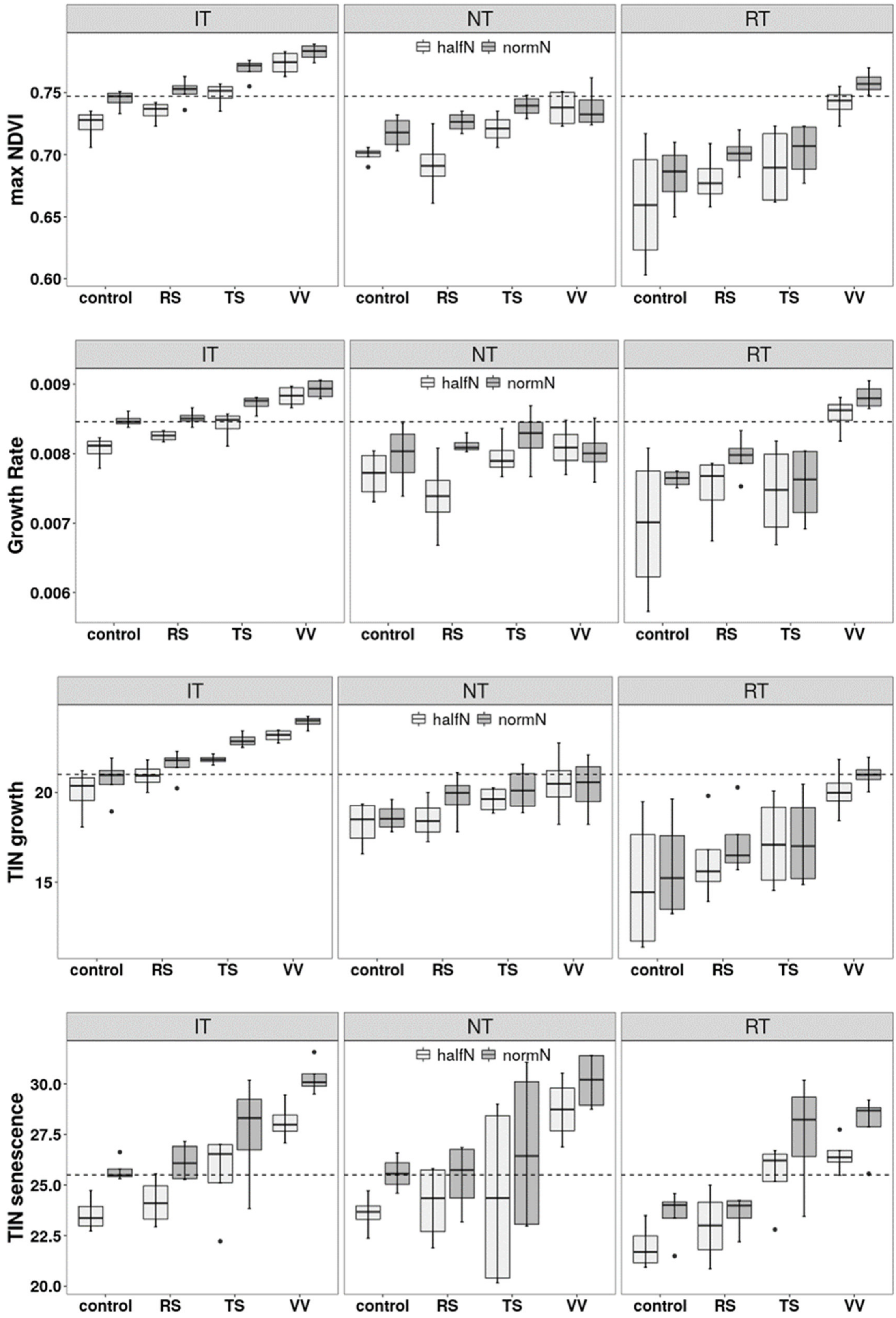

**Supplementary Figure S1:** Mean temperature and sum of precipitations of the growing seasons of cover crops and maize for Experiment I and II.



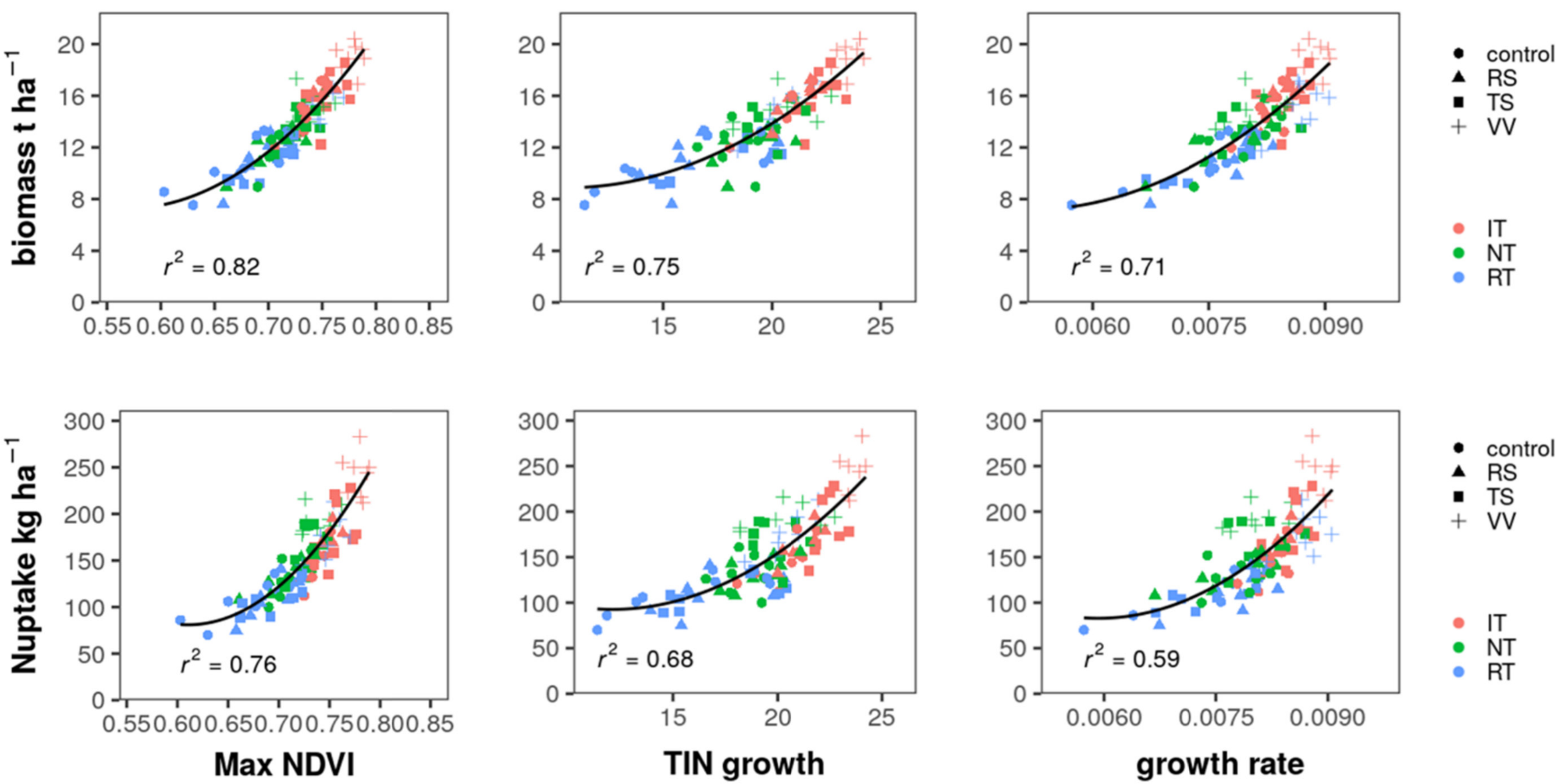

**Supplementary Figure S2:** Maize grain yield for the main factors within each experiment I and II (year). Different letters indicate significant differences between treatments within one experiment (Tukey test, $p<0.05$). Only the interaction between experiment and fertilization is significant. For statistical details see Table 1 in the original article. IT: intensive tillage, NT: no tillage, RT: reduced tillage / control: no cover crop, RS: oilseed radish, TS: subterranean clover, VV: hairy vetch / normN: norm fertilization, halfN: half fertilization.




**Supplementary Figure S3:** Relationship between maize N uptake and the N nutrition index (NNI). An NNI above 1 indicates no N limitation for the crop. IT: intensive tillage, NT: no tillage, RT: reduced tillage / control: no cover crop, RS: oilseed radish, TS: subterranean clover, VV: hairy vetch




**Supplementary Figure S4:** Maize growth phenological parameters (n=4) in four cover crop treatments (control; oilseed radish (RS); subterranean clover (TS); hairy vetch (VV)) under intensive tillage (IT), no tillage (NT) and reduced tillage (RT) and norm and half fertilization. The dashed lines represent the mean value of the reference treatment with intensive tillage, norm fertilization and no cover crop.




**Supplementary Figure S5:** Correlation (polynomial regressions second order) between crop growth parameters calculated from UAV imagery and maize biomass and N uptake (Max NDVI: maximal NDVI value, TINgrowth: Time Integrated NDVI until 76 days after sowing (half growing period)). (IT: intensive tillage, NT: no tillage, RT: reduced tillage) (control: no cover crop, RS: oilseed radish, TS: subterranean clover, VV: hairy vetch).

# GENERAL DISCUSSION

Global demand for food, feed and energy derived from agricultural land is forecasted to double within the next decades, driven by population growth, rising per capita income and increased consumption of animal products (Tilman *et al.*, 2011). Current economic systems and world market regulations still push agricultural production to further intensification, keeping production costs low and worsening the impact of agriculture on the environment. Continuous deforestation of the Amazon (DeFries *et al.*, 2010; FAO, 2020) to sustain protein supply for livestock production worldwide or exponentially growing intensive aquaculture systems which dramatically impair aquatic ecosystems (Naylor *et al.*, 2001; Naylor *et al.*, 2005) are only two examples among many. Finding alternative farming systems to improve sustainability of agricultural production at various levels of the food system thus remains a major challenge.

This dissertation deals with the potential improvement of the sustainability and multifunctionality of arable cropping systems. Built on the comprehensive analysis of the long-term FAST experiment, I applied the concept and methods behind ecosystem multifunctionality to assess and compare the overall performance of conventional, organic and soil conservation cropping systems at the field level. Next, I investigated the potential of cover crops, as an ecological intensification measure, to improve the performance of the investigated systems. In the following, I discuss the results in light of the current knowledge and the potential to implement these practices in current agricultural production systems and policies.

## The productivity – environment dilemma, beyond system boundaries

My results highlight and confirm that a reduction in environmental footprint is generally coupled with either a decrease of productivity or higher yield variability (Gabriel *et al.*, 2013). Both conservation and organic agriculture improved supporting and regulating services, but conventional production still provided the highest yields. In fact, none of the investigated systems performed best in all ecosystem functions within their fixed boundaries (Figure 1).

Conventional no tillage cropping largely fulfilled his objectives in terms of soil quality and soil protection improvement without significant yield losses (Wittwer *et al.*, 2017) (chapter 1). Higher soil aggregation (Puerta *et al.*, 2018) together with permanent soil cover reduced erosion risk by 93% compared to intensive tillage (Seitz *et al.*, 2018). It also promoted soil organisms such as earthworms, AMF (chapter 1) and overall fungi abundance (Wagg *et al.*, 2018) as well as affected microbial community composition (Hartman *et al.*, 2018). However, it marginally affected other important environmental impact categories such as greenhouse gas (GHG) emissions and aquatic ecotoxicity potential (Prechsl *et al.*, 2017), because mineral fertilizers were applied and herbicides were more frequently used.

Similar effects on soil quality were achieved under traditional organic cropping with regular ploughing (Hartman *et al.*, 2018; Puerta *et al.*, 2018) but organic management also reduced GHG emissions and improved water protection (Prechsl *et al.*, 2017). However, erosion risk was higher as under no tillage, even if lower than conventional management and intensive tillage (Seitz *et al.*, 2018). Moreover, lower fertilizer use efficiency from the applied slurry and a higher weed pressure resulted in an average of 25% yield loss compared to conventional cropping (Wittwer *et al.*, 2017) (chapter 1).

Innovative organic cropping with conservation tillage showed in many cases a synergistic effect on soil and environmental quality parameters. It successfully reduced erosion risk (Seitz *et al.*, 2018), showed highest values for soil aggregation (Puerta *et al.*, 2018) and soil biota abundances (chapter 1) and reduced surface based GHG emissions as well as nutrients and pollutants losses (Prechsl *et al.*, 2017). However, difficulties related to successful weed control, especially perennial grasses in this case, resulted in higher yield losses (- 35% compared to conventional cropping) and cancelled air and water protection benefits on a productivity basis (Prechsl *et al.*, 2017) (chapter 1).

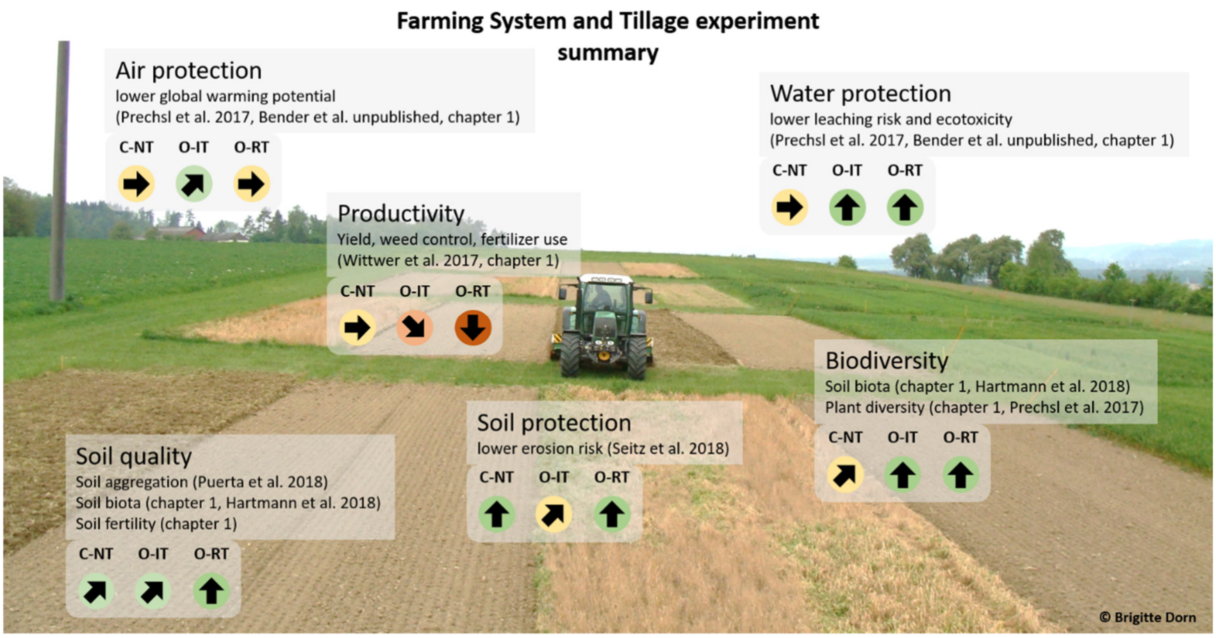



**Figure 1: Graphical summary of the Farming System and Tillage experiment** and the qualitative impacts of three alternative cropping systems (C-NT: conventional no tillage, O-IT: organic intensive tillage, O-RT: organic reduced tillage) compared to conventional production with tillage on agronomical and ecological variables.

These findings point to the need to clearly define which services agriculture should deliver, a goal also articulated for other ecosystem types (Allan et al. 2015; Manning et al. 2018), and how service delivery should be allocated considering the land sparing versus sharing debate. Even if land sparing (the separation of ecosystem delivery, e.g. in intensive high production areas and conservation hotspots) offer advantages, it was shown that an important degree of land sharing (combining different services) would be the best option in Europe (Herzog and Schüepp, 2013).

Yet, organic and no-tillage systems represent each about 5% of total arable land in Switzerland, and 1.5% and 12.5% respectively worldwide (Kassam *et al.*, 2018; Willer and Lernoud, 2019). Thus, if environmental protection and an increase in supporting and regulating services (i.e. biodiversity conservation, mitigation of climate change and reduction of soil erosion), is a priority for agricultural land, this would require a substantial expansion of such systems. It is clear that there is no panacea for the very diverse contexts and environments agriculture faces. Moreover, there is still high uncertainty in upscaling organic and conservation agriculture (Meier *et al.*, 2015; Seufert and Ramankutty, 2017). However, there is evidence that other improvements could contribute to maintaining current productivity besides the broader adoption of organic or conservation agriculture. Key prerequisites are spatially redistributed cropland, improved water–nutrient management, food waste reduction and dietary changes (Gerten *et al.*, 2020).

Indeed, present production volumes could be maintained by reducing yield gaps through optimized fertilization and crop allocation across global cropland and at the same time reducing by nearly 50% actual cropland area. Combined with land sparing for biodiversity hotspots and allotting an additional 20% of cropland area for other landscape elements would still enable a reduction of cropland requirements by almost 40% (Folberth *et al.*, 2020). On the other hand, adjusting diets according to current nutritional recommendations (WHO *et al.*, 2004; EFSA, 2020) would allow a reduction in production by 30% for plant products and 40% for animal products, sparing land for agro-ecological infrastructures and still providing sufficient food for the European population (Poux and Aubert, 2018). Thus, besides improving farming systems at the field or farm level (discussed below), a great deal could be achieved by a re-organization of the food system and changes in consumer behavior, which in turn decrease the pressure imposed on farmers.

**Drawbacks and limits of organic and conservation agriculture**

Even if organic farming and conservation agriculture offer several benefits, it also has important limits, which should be equally considered as an improvement of intensive agriculture. Organic farming successfully promotes reliable environmental benefits, but numerous meta-analyses have concluded that yields under organic management are, on average, 19 to 25% lower than under conventional management (de Ponti *et al.*, 2012; Seufert *et al.*, 2012; Ponisio *et al.*, 2015). In addition, greater reliance on ecological processes may reduce predictability of crop production (Smith *et al.*, 2019). Indeed, organic productivity shows a 15% decrease in yield stability compared to conventional farming (Knapp and van der Heijden, 2018). This was mostly attributed to variable and unpredictable nutrient availability, although the use of green manure and overall enhanced fertilization was shown to improve the temporal production stability of organic systems.

The majority of studies included in those meta-analyses originate from developed countries where lower stability can be buffered by higher inputs, price premiums and agricultural policies, which is not always the case in developing countries where food security is a major priority and where the majority of producers are located (Seufert and Ramankutty, 2017). Whereas one can argue that organic farming can be more resilient to stresses (abiotic and biotic) and be a valuable improvement in regions where access to inputs are limited, this remains largely unknown. Thus, increasing yields and reducing yield variability remains a major challenge for organic agriculture in order to increase the environmental performance per unit output and deliver higher insurance for farmers.

As for organic agriculture, conservation agriculture offers several benefits, not only in terms of soil quality improvements but also reduced workloads and costs. Contrarily to organic farming, it does not result in high productivity losses but often relies on synthetic inputs. The availability of herbicides suitable for control of a wide range of weed species is still a paramount requirement for many no-till systems. Thus, a majority of no tillage acreage is dependent on herbicides (Triplett and Dick, 2008), which is particularly true when GMOs are grown (e.g. GM soybean in South America). The introduction of glyphosate (Roundup) in 1971 brought many advantages and allowed the rapid expansion of no tillage but its utilization is more and more criticized by society as concerns about negative health and environmental impacts emerge. Besides unknown or unclear negative effects on the environment and human health, the repetitive and frequent use of herbicides (and other pesticides) results in resistance to an important number of compounds and could threaten the effectiveness of no-till systems dependent on herbicides (Triplett and Dick, 2008). Decreasing herbicide dependency of conservation tillage systems stays a major challenge. In my analyses, the no tillage system displayed the most balanced measure of function delivery but it is unclear how it would perform if pesticides and mineral fertilizer applications would be limited (Lundy *et al.*, 2015).

**Managing trade-offs by ecological intensification**

Increases of productivity since the Green Revolution have been realized through an increase of external, mostly synthetic, inputs. This, together with its counterpart (i.e. the development of extensive production such as organic agriculture), resulted in this strong productivity-environmental protection dilemma, highlighted in chapter 1. Most agricultural research now focuses on alternative practices that could maintain or increase productivity with less negative environmental impacts under the umbrella of sustainable or ecological intensification and agroecolgy. The goal is to design agro-ecosystems that make maximum use of natural processes such as improved soil biota functioning, natural nitrogen fixation or the recycling of resources. In chapters 2 and 3, I particularly looked at the effects of cover crops as ecological engineering tools to improve the sustainability of arable production. I could demonstrate that their inclusion in crop rotations can help over a wide range of management intensities. Indeed, cover cropping can increase the productivity of more extensive systems where inputs are limited (ecological enhancement) as well as reduce input needs without compromising yields in systems that are more intensive (ecological replacement) (Figure 2).

The analyses of the effects of cover crops within the cropping systems of the FAST experiment in chapter 2 have highlighted the relationship between management intensity and the resulting benefits of cover cropping. Significant yield improvement and weed control were only visible when management intensity was decreased. Thus, if clear benefits from cover crops should be attained, this implies that a reduction of external inputs is also required, otherwise these inputs would overshadow the positive effects of cover crops. This also applies for all kinds of ecological replacement measures.

In chapter 3, I demonstrated that leguminous cover crops can be used to partly replace fertilizer inputs without compromising yields under intensive and no tillage management, and thus confirms that cover cropping has the ability to facilitate conservation agriculture and more extensive cropping practices. Combined with sufficient weed suppression (in general not only for legume species), it was also possible to reduce herbicide use. Cover crops are a crucial element of CA systems which help to reach an appropriate soil coverage during fallow period, promote soil fertility, maintain productivity, and open possibilities to reduce herbicide dependency (Hartwig and Ammon, 2002; Pittelkow *et al.*, 2015; Marcillo and Miguez, 2017; Wittwer *et al.*, 2017; Büchi *et al.*, 2018). Cover crops are also important in organic systems, mainly as a source of nitrogen and for the recycling of nutrients.

Overall, this work demonstrates that cover crops are a suitable tool for ecological engineering, but that the effects vary depending on other cropping practices. Thus, I recommend that farmers and farm advisors consider the whole set of cropping practices when adopting specific cover crops in order to maintain or increase productivity but reduce input needs and costs. Only if the maximum potential of environmentally friendly replacement of anthropogenic inputs is reached, a broader adoption and acceptance of such practices could be achieved.

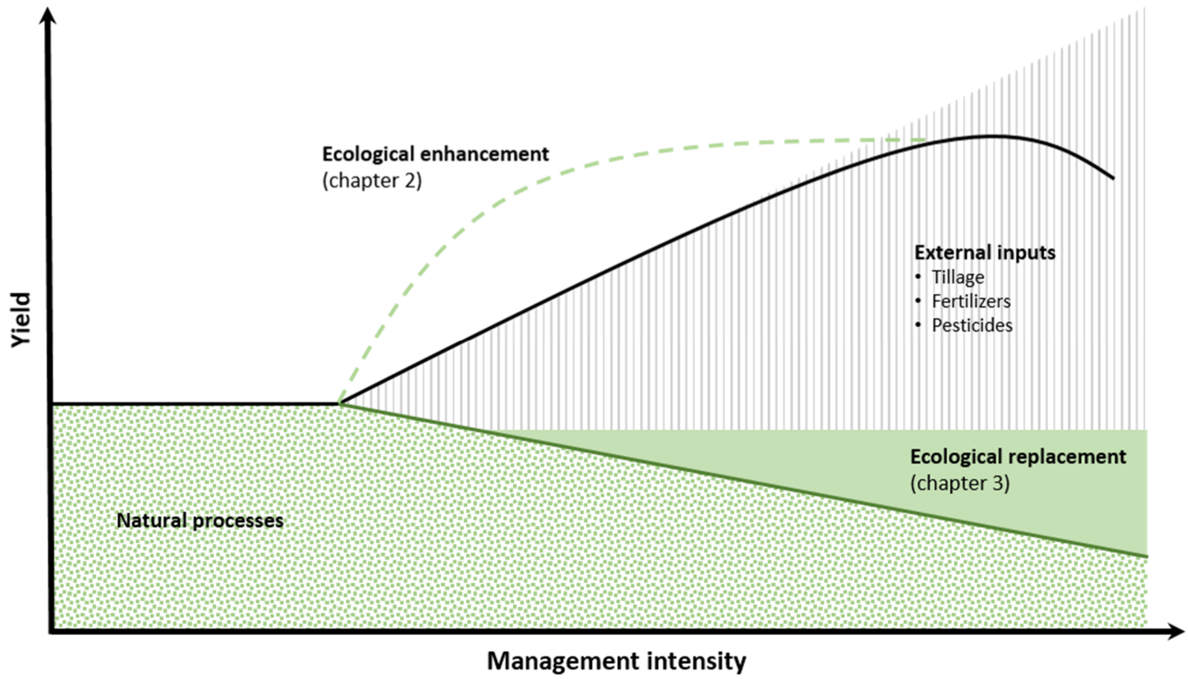



**Figure 2: Conceptual summary of the benefits of cover cropping in terms of ecological intensification**. Natural processes sustain a given yield, which increase as a function of management intensity with increasing external inputs, which generally overweight natural processes and decrease their contribution to yield. Cover crops can act as ecological enhancement measure by increasing yield with limited inputs or ecological replacement by decreasing inputs needs (fertilization, tillage intensity or pesticides) but maintain yield level.

As for any changes or implementation of new practices, it is important not only to look at potential benefits but also be aware of potential drawbacks. In the case of cover cropping, potential phytopathological risks by including main crop related species could arise (Finckh *et al.*, 2015). For example, the repeated use of legumes as cover crops could potentially increase important soil-borne pathogens. Within the coordinated EU-project OSCAR (Optimizing Subsidiary Crops Applications in Rotations), we have found that legume species have the potential to harbor important pest and disease, as shown for nematodes (Schmidt *et al.*, 2017) and for *Fusarium* fungi (Walder *et al.*, 2017; Šišić *et al.*, 2018). Thus, their repeated use should be planned with caution. On the other hand, these risks, as well as the amount of N delivered by cover crops, could be managed by using mixtures of species which make use of their associated multiple services (Amosse *et al.*, 2015; Tribouillois *et al.*, 2015; Finney *et al.*, 2017; Couëdel *et al.*, 2018). Indeed, mixing different species act as insurance, often outcompete monoculture (e.g. for biomass production) and often provides multiple functions.

Cover cropping is just one of many different practices that can contribute to ecological intensification. Crop rotation, the application of organic amendments (manure and compost) and some forms of conservation tillage are already widely adopted practices in different contexts (Barão *et al.*, 2019). Often, these practices are implemented in the perspective of maintaining or improving soil fertility and quality and are important pillars of both conservation and organic agriculture (Ponisio *et al.*, 2015; Martínez *et al.*, 2016; Hijbeek *et al.*, 2017; Maltas *et al.*, 2018; Degani *et al.*, 2019; Krauss *et al.*, 2020). It is widely recognized that conservation and organic agriculture improve soil biota (Lori *et al.*, 2017; Chen *et al.*, 2020). However, many questions remains on how this affects soil functioning and our ability to operate targeted microbiome changes (Hartman *et al.*, 2018; Wagg *et al.*, 2018). The concept of soil ecological engineering developed by Bender *et al.* (2016) highlight the central role of soil organisms and the potential contribution of increased biological diversity with targeted manipulations of soil biota to enhance overall ecosystem service delivery and minimize yield gaps. However, this aspect is often overlooked and would deserve greater attention.

Innovative systems are known to be more variable compared to established systems and often result in failure and frustration due to lack of know-how. Adaptation time since conversion, increased knowledge, experience, and technological advances often positively influence system control and performance. In the case of the FAST experiment, we can already observe a yield gap decrease for the organic systems compared to the conventional systems along the second crop rotation (Figure 3). It is too early to be able to attribute this yield increase in the organic systems to an improvement of soil quality or to improved field management (e.g. weed control), but these results highlight that research and policy should support farmers in the transition phase following adoption of innovative management practices.

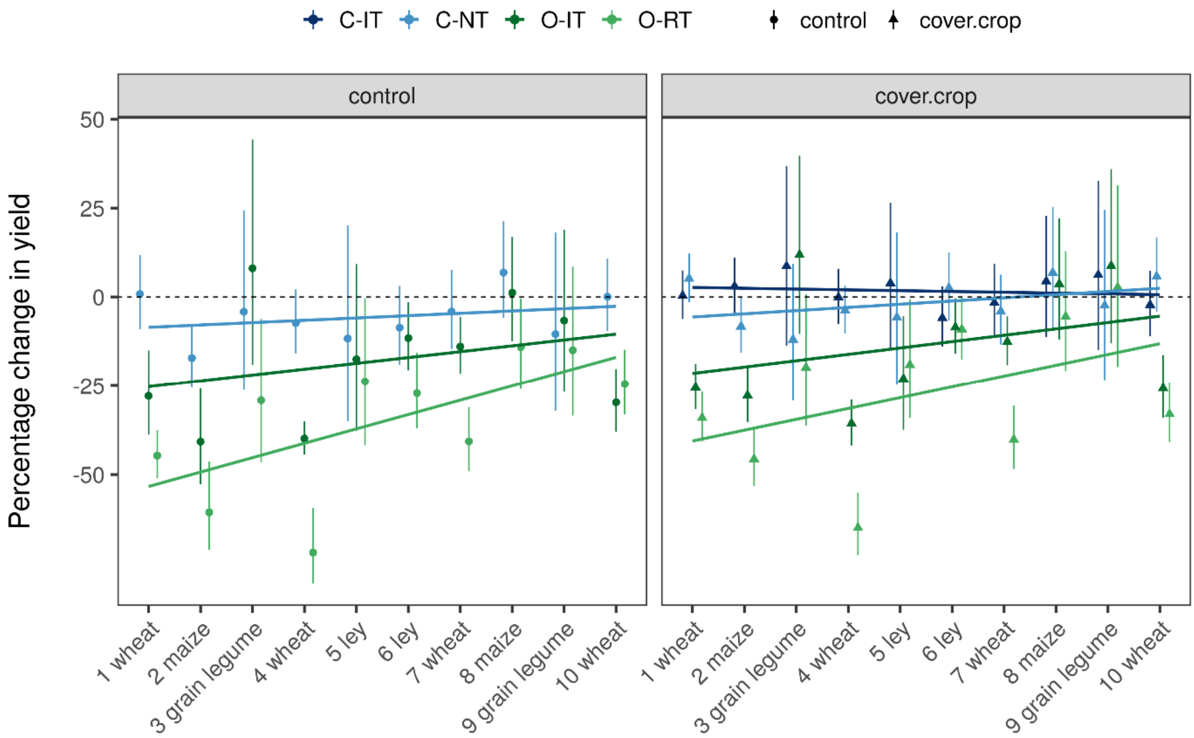



**Figure 3: Yield difference (%), with and without cover crops, compared to the conventional intensive tillage system with no cover crops (0) along the crop rotation of the FAST experiment (2009 - 2019)**. Yield differences displayed as means of the back-transformed log response ratios (Viechtbauer, 2010). Mean ± confidence intervals (CI) of the effect sizes are displayed. Treatments are significantly different from the reference system if CIs do not overlap zero. Lines represent linear regression fits of yield difference along years since begin of the experiment.

### Implementing multifunctionality assessments

Providing suitable assessment tools for farmers and policy makers that help to improve and monitor the sustainability and multifunctionality of agriculture would be a clear benefit. However, currently such integration has not found its way into practice. Although, there is growing recognition that agriculture can provide additional ecosystem services beyond the provision of food and feed (Swinton et al. 2007, Power 2010) and would potentially allow society to pay for improvements in services provided by farming, it is still a challenge to monetarize services such as a clean water supply, biodiversity conservation, climate mitigation, or soil protection and integrate such costs into product prices. Additionally, the negative environmental impacts of agricultural practices are costs that are typically unmeasured (Tilman *et al.*, 2002) and are usually externalized, being greater for society as a whole than for the farms on which they operate (Stoate *et al.*, 2001). As such, these impacts often do not influence farmer or societal choices about production methods and thus do not result in real changes to the food system. At a policy and national level, key economic indicators such as gross domestic product (GDP) were shown to be insensitive to the integration of alternative environmental-economic evaluations that would account for environmental costs and thus also limit the potential of classic economic metrics to achieve real changes (Polasky *et al.*, 2015).

In contrast, agro-environmental policies play a major role in shaping agricultural practices (Bjørkhaug and Richards, 2008). This is particularly true in Switzerland were a direct payment system (subsidies) was already introduced in the 1990's to improve the ecological performance of agriculture (Proofs of ecological performance), which include, amongst others, mandatory crop rotations, regulated nutrient balances and appropriate soil protection measures. Also at the European level, the further development of the Common Agricultural Policy (CAP) have tried to drive agriculture to a more ecological state (Stoate *et al.*, 2009). The main reforms in both cases were the decoupling of subsidies from production, the introduction of cross-compliance and the development of agri-environment programs with more or less success.

Decoupling of payments from production and allocating it to area was a major change that should reduce further intensification. However, it turned out that in was more beneficial for big producers than small ones (Stoate *et al.*, 2009). As a result, in some regions marginal land tends to be abandoned and in arable land greater simplification can be observed with increases in crops with the highest net marketable value (Stoate *et al.*, 2009).

Cross-compliance payments are linked to good agricultural practices that are in accordance with environmental protection, public health or animal welfare. The Proof of Ecological Performance in Switzerland is one example of cross-compliance, which has been shown to be effective in reducing nitrogen (N) and phosphorus (P) losses from agriculture but did not reach all goals at once (Herzog *et al.*, 2008). Environmental benefits arising from cross-compliance are few and mainly based on expert judgement rather than direct measurement of environmental outcomes (Stoate *et al.*, 2009). Moreover, the measures required in Switzerland are far stricter than in many other EU countries.

Agri-environment programs aim to enhance the ecological status of farmland through soil conservation, biodiversity conservation, and reduction in water pollution. The participation in such programs is generally on a voluntary basis and has been shown to increase the awareness of farmers about the environment besides improving environmental targets. However, their efficacy could not always be demonstrated (Kleijn *et al.*, 2001; Kleijn *et al.*, 2006) and measuring these effects is still difficult due to the great variability of the practices implemented in different regions, delayed response and the lack of efficient monitoring (Tscharntke *et al.*, 2005).

Despite efforts to improve the environmental sustainability of agricultural systems with agricultural policies, intensification and abandonment are still observed (Reidsma *et al.*, 2006) and quantifiable effects are difficult to assess due to the lack of monitoring and tools. Moreover, incentives are often linked to the use of specific practices but not on quantifiable goals or achievements. Much of this lack of progress can also be attributed from the large gap between the work of scientists on ecosystem services and the needs of policy makers and managers to apply these concepts into practice (Polasky *et al.*, 2015).

In chapter 1, I choose to apply the concept and methods of the ecosystem multifunctionality approach increasingly applied in the field of ecology to compare service delivery of different cropping systems. The multifunctionality indices showed a strong dependency upon the weighting of the individual functions, and trade-offs were strongly hidden when averaged into a single value, underlying the importance of assessing tradeoffs among multiple functions. It is important to acknowledge that within my analysis I did not specifically include 'natural' or 'theoretical' thresholds above which a system can be said to be multifunctional. Therefore, the virtue of this work was not directly to categorize or label whole systems as multifunctional or not, as agriculture intrinsically has multiple outcomes (positive or negative). Instead, the value of the multifunctionality analysis of the FAST experiment lies in the possibility it offer to compare cropping systems and identify trade-offs and key leverage options.

An important aspect to consider in EMF analyses is the integration of realistic scenarios, in which ecosystem functions or services are weighed according to specific objectives (Allan *et al.*, 2015) or the integration of some baseline values at which a certain function is supposed to be performed in order to be considered functional (van der Plas *et al.*, 2016). Thus, an important improvement would be the integration of reference values (objectives, limit values) in EMF analyses, such as the investigated systems are not only compared among each other within a particular study, but also against a representative state or goal at the desired time and spatial scales. However, such an approach requires normative values that could be subjective, vary among stakeholders or are simply missing, which is also true for choosing appropriate thresholds. This exercise is beyond the scope of this thesis, but would be an important step forward into the broader implementation of such analyses.

In chapter 1, I computed various EMF indices and developed an interactive web application, which makes it possible to weigh individual functions according to different scenarios and visualize trade-offs among different ecosystem services. A further development of this tool, by integrating adequate indicators (largely applicable, data are available) and standard values, could help researchers, farmers or policy makers to evaluate different management practices and design policy instruments.

Figure 4 illustrates a possible way to integrate multifunctionality assessments into agricultural policy design and support sustainability at the farm level involving policy makers, research and farmers. As a prerequisite, appropriate standards for ecosystem functions and services should be set and agreed on so that policies could define clear objectives (1). Additionally, appropriate indicators should be developed that are widely applicable and act as reliable proxies for ecosystem functions (2). In Switzerland, different monitoring programs are conducted such as the national soil monitoring service (NABO), the agri-environmental indicators (AOU) or the Farm Accountancy Data Network from Agroscope. These, together with evidence from long-term farming system experiments and the democratization and transparency of life cycle analysis methods, could offer a solid basis for the development of suitable indicators and models to implement in multifunctionality analysis tools (Lüscher *et al.*, 2017). Combined with the stated objectives and data from the farms, an evaluation of multifunctionality and the achievement or failure of specific objectives could be performed (3). Based on these findings, adapted incentives could be developed in order to improve farm performance and the fulfillment of the objectives (4). As a dynamic process, each of these steps are not static and allow the continuous evaluation and improvement of indicators, objectives, farm performance and incentives (↻).

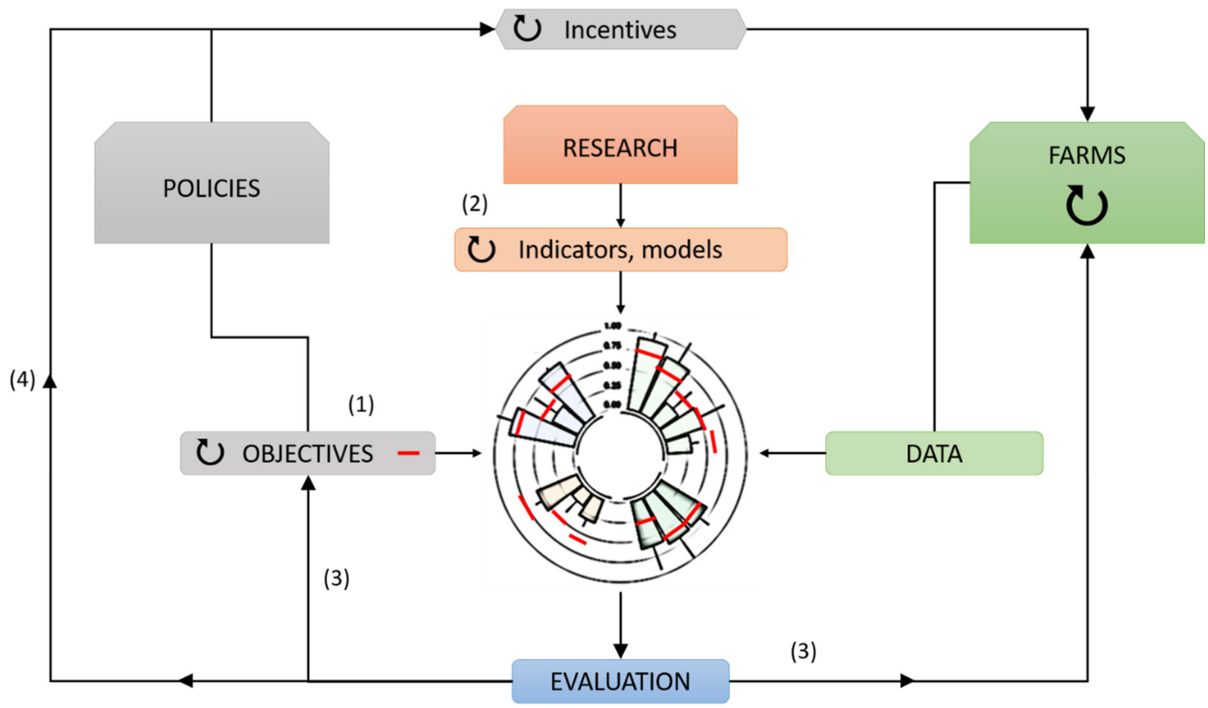



**Figure 4: Conceptual framework for the implementation of an assessment tool to evaluate farm/cropping system performance, incentive performance or objective achievement**. Stated objectives (1) and appropriate indicators (2) should be integrated in multifunctionality assessment to evaluate farm performance and objectives achievements (3) and allow the development of targeted incentives (4) in a dynamic optimization process.

This concept is not limited at the farm level but could be applied at a regional or national scale to evaluate more broadly the performance of agricultural production by combining the concept with special distribution of acreage and production systems. However in each application case and level, the use of standards should clearly define i) terminology and context, ii) data and methods used for services delivery and iii) how the service valuation is assessed (Polasky *et al.*, 2015). Whereas the general terms and concepts could be relatively easily agreed upon and the data and methods used could be adaptable to improvements, the main challenges und uncertainties remain in the monetarization of service values (e.g. incentive amounts) and the appropriate choice of threshold values (objectives).

Such an evaluation and regulation scheme would imply a strong policy driven agricultural production, which contrasts to classic market regulation. Both have their advantages and limits as described above, but until now classic economic regulation have not been shown to achieve real changes (Kinzig *et al.*, 2011). Improved monitoring and evaluation of agricultural policies based on impact assessment, like proposed, would be a next frontier to cross in the development of a sustainable agriculture.

An important aspect to consider in an international context and globalized food system are the system boundaries of the evaluation (farm, country, imports, exports, etc.) and other drivers that influence food demand. As an example, Bene *et al.* (2019) recently analyzed food system sustainability based on an similar approach and investigated potential drivers that influence overall the sustainability score (Bene *et al.*, 2020). They found that in addition to short-term acute shocks, long-term global demographic changes like urbanization and population growth may be obstacles to improving food system sustainability. Thus, the social, economic and cultural dimensions, as well as a better understanding of the contrasting contexts in which decision-making occurs are key components to achieve sustainability (Cavender-Bares *et al.*, 2015).

## Conclusions

In summary, I found that alternative farming systems such as organic and conservation agriculture offer ecological advantages compared to conventional production, as they improve the delivery of supporting and regulating services and promote ecosystem multifunctionality. However, the increase in environmental benefits was coupled with a decrease in productivity, while the conventional cropping system promoted provisioning services and delivered the highest yields. Overall, the multifunctionality indices showed a strong dependency upon the weighting of the individual functions and revealed important trade-offs.

A possible way to counteract the productivity-environmental protection dilemma is to introduce ecological practices into current cropping systems. My results highlight that the inclusion of cover crops in the rotation provides additional opportunities to increase the yields in cropping systems with lower management intensity (i.e. where inputs are limited), as well as reduce input needs without compromising yield in systems that are more intensive. Indeed, cover crop effects varied depending on the combination with other cropping practices but generally positive effects increased when management intensity was reduced. In particular, the use of leguminous cover crops can be used to partly replace fertilizer inputs without compromising yields under intensive and no tillage management, as well as substantially increase yields under organic management.

I conclude that future cropping systems must be designed to achieve clearly defined goals, and that all available best practices should be taken into consideration in order to overcome system boundaries and achieve greater multifunctionality. This is because trade-offs between high productivity and environmental protection, although manageable to a certain extent, are inevitable. Ecological intensification practices can help to moderate these trade-offs but should be an integrated part of the management strategy and not be seen as a standalone solution, as demonstrated in the case of cover crops.

Providing tools to improve the multifunctionality and sustainability of agriculture by supporting farmers and policy decisions would be an important step forward. A closer collaboration between the scientific community and public and private organizations (policy makers and managers) to set standards for the evaluation of agricultural systems, or more generally the food-system, would foster the implementation of incentives that account for ecosystem delivery and allow the evaluation and improvement of these incentives themselves.

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# SUMMARY

One of the primary challenges of our time is to develop sustainable farming systems that can feed the world with minimal environmental impacts. For the design of sustainable production systems, it is important to recognize that agro-ecosystems supply multiple functions simultaneously and provide various services to human. Organic and conservation agriculture are today the most prominent alternatives to intensive arable systems. Organic agriculture prohibit the use of synthetic inputs (pesticides and fertilizers) and a range of studies show that organic farming enhances biodiversity and has reduced environmental impact. Conservation agriculture, in turn, is based on three main pillars: minimum mechanical soil disturbance, permanent soil cover and species diversification. Several studies indicate that conservation agriculture has positive effects on soil quality and protection, water regulation, energy use and production costs. Despite these advantages, both approaches have also limits, mainly concerning lower productivity. However so far, systematic evaluations to assess the overall performance of different cropping systems are scarce.

This dissertation deals with the potential improvement of the sustainability and multifunctionality of arable cropping systems. Built on the comprehensive analysis of the long-term Farming System and Tillage (FAST) experiment, comparing four important cropping systems since 2009, I applied the concept and methods behind ecosystem multifunctionality to assess the overall performance of conventional, organic and soil conservation cropping systems at the field level. Out of 41 assessed parameters, I derived 14 ecosystem functions and computed various ecosystem multifunctionality indexes to assess the overall performance of the investigated cropping systems (chapter 1). Next, I investigated more specifically the role of cover crops as an ecological tool in supporting ecological intensification of arable cropping systems. Cover crops are often recommended as a valuable practice to develop more sustainable cropping systems but, despite many benefits, their adoption in practice is still limited mainly because the effects on productivity and economic return are variable. Furthermore, it is still unclear under which combinations with other management practices (e.g. tillage, fertilization, weed control) cover crops can provide the highest paybacks. Particular emphasis was given to cover crops and their ecological functions in the agroecosystem and how these functions are expressed within different cropping systems (Chapter 2) as well as their ability to reduce anthropogenic inputs in intensive cropping systems by reducing tillage, fertilization and herbicide intensities (Chapter 3). The aim was to optimize the internal regulation of nutrients, weed control and crop diseases by integrating environmental-friendly management practices in arable cropping systems but sustain productivity.

This research demonstrates that organic and conservation agriculture promoted ecosystem multifunctionality, especially by promoting regulating and supporting services including biodiversity, soil quality as well as climate, water and soil protection. However, an increase in environmental benefits was often coupled with a decrease in productivity and the conventional intensive cropping systems still delivered highest yields. The multifunctionality indexes showed a strong dependency upon the weighting of the individual functions and revealed important trade-offs among individual ecosystem functions, service categories and cropping systems pointing to the need to clearly define which services agriculture should deliver.

A possible way to counteract the productivity-environmental protection dilemma is to introduce ecological practices into current cropping systems. My results highlight that the inclusion of cover crops in the rotation provides additional opportunities to increase the yields of production systems with lower management intensity, where inputs are limited, as well as reduce input needs without compromising yield in systems that are more intensive. Indeed, cover crop effects varied depending on the combination with other cropping practices but generally positive effects increased when management intensity was reduced. Particularly the use of legume cover crops can be used to partly replace fertilizer inputs (up to 50%) without compromising yield under intensive and no tillage as well as substantially increase yield under organic management.

I conclude that future cropping systems must be designed to achieve stated objectives (e.g. production volume, environmental protection levels) that should clearly define what set of services and at which level by making use of all available best practices beyond system boundaries. This because trade-offs between high productivity and environmental protection, although manageable to a certain extent, are inevitable. In order to support farmers, stated goals should be supported by politic and society in order to value the delivery of other services than productivity. Research, on the other hand, should support the process by delivering and optimizing suitable indicators and assessment tools. Providing tools to improve the multifunctionality and sustainability of agriculture by supporting farmers and policy decisions would be an important step forward in the design of sustainable agricultural systems. A closer collaboration between the scientific community and public and private organizations (policy makers and managers) to set standards for the evaluation of agricultural systems, or more generally the food-system, would foster the implementation of incentives that account for ecosystem delivery and allow the evaluation and improvement of these incentives themselves.

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# CURRICULUM VITAE


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**Education**

B.Sc. in Agricultural Science, 2009. Eidgenössische Technische Hochschule Zürich (ETHZ)

Thesis: *"Induced resistance in apple: kinetics of resistance expression and influence of leaf age"*

Professional Internship, 2010. International Center for Tropical Agriculture (CIAT), Cali, Colombia.

Topic: *"Bruchid resistance in common bean: development of improved varieties by Marker Assisted Selection"*

M.Sc. in Agricultural Science, 2011. Eidgenössische Technische Hochschule Zürich (ETHZ). Major in Plant science.

Thesis: *"Breeding for leaf rust resistance: Impact and risk of reintroducing the quantitative resistance gene Lr34 in Swiss winter wheat"*

Ph. D. 2020. Institute of Evolutionary Biology and Environmental Science, University of Zürich. PhD program in plant science, Plant-Science-Center.

Thesis: *"Assessing and Improving the Multifunctionality of Swiss Arable Cropping System"*

**Publications**

**First Author**


**Wittwer**, R.A., van der Heijden, M.G.A., 2020. Cover crops as a tool to reduce reliance on intensive tillage and nitrogen fertilization in conventional arable cropping systems. Field Crops Research 249.

**Wittwer**, R.A., Dorn, B., Jossi, W., Van Der Heijden, M.G., 2017. Cover crops support ecological intensification of arable cropping systems. Scientific reports 7, 41911.

**2019**

Reimer, M., Ringselle, B., Bergkvist, G., Westaway, S., **Wittwer**, R., Baresel, J.P., van der Heijden, M.G.A., Mangerud, K., Finckh, M.R., Brandsæter, L.O., 2019. Interactive Effects of Subsidiary Crops and Weed Pressure in the Transition Period to Non-Inversion Tillage, A Case Study of Six Sites Across Northern and Central Europe. Agronomy 9.

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Seitz, S., Goebes, P., Puerta, V.L., Pereira, E.I.P., **Wittwer**, R., Six, J., van der Heijden, M.G.A., Scholten, T., 2018. Conservation tillage and organic farming reduce soil erosion. Agronomy for Sustainable Development 39, 4.

Radicetti, E., Baresel, J., El-Haddoury, E., Finckh, M., Mancinelli, R., Schmidt, J., Alami, I.T., Udupa, S., van der Heijden, M., **Wittwer**, R., 2018. Wheat performance with subclover living mulch in different agro-environmental conditions depends on crop management. European Journal of Agronomy 94, 36-45.

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Papp, R., Marinari, S., Moscatelli, M., van der Heijden, M., **Wittwer**, R., Campiglia, E., Radicetti, E., Mancinelli, R., Fradgley, N., Pearce, B., 2018. Short-term changes in soil biochemical properties as affected by subsidiary crop cultivation in four European pedo-climatic zones. Soil & Tillage Research 180, 126-136.

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**2017**

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Schmidt, J., Bergkvist, G., Campiglia, E., Radicetti, E., **Wittwer**, R., Finckh, M., Hallmann, J., 2017. Effect of tillage, subsidiary crops and fertilisation on plant-parasitic nematodes in a range of agro-environmental conditions within Europe. Annals of Applied Biology 171, 477-489.

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**2016 and older**

Cooper, J., Baranski, M., Stewart, G., Nobel-de Lange, M., Bàrberi, P., Fließbach, A., Peigné, J., Berner, A., Brock, C., Casagrande, M., Crowley, O., David, C., De Vliegher, A., Döring, T.F., Dupont, A., Entz, M., Grosse, M., Haase, T., Halde, C., Hammerl, V., Huiting, H., Leithold, G., Messmer, M., Schloter, M., Sukkel, W., van der Heijden, M.G.A., Willekens, K., **Wittwer**, R., Mäder, P., 2016. Shallow non-inversion tillage in organic farming maintains crop yields and increases soil C stocks: a meta-analysis. Agronomy for Sustainable Development 36, 1-20.

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## Other published works and contributions

van der Heijden M.G.A and **Wittwer** R.A., 2017. A comparison of Swiss arable cropping systems: an agronomic, environmental and ecological evaluation. In: Agriculture in Transformation. Concepts for agriculture production systems that are socially fair environmentally safe: Proceedings of the PSC Summer Schools 2014 and 2016. Idea Verlag.

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Amosse, C., Dugon, J., Chassot, A., Courtois, N., Etter, J.-D., Fietier, A., Gruenig, K., Henggartner, W., Ramseier, H., Rossier, N., Sturny, W., **Wittwer**, R., Zimmermann, A., Jeangros, B., Charles, R., 2015. Verhalten verschiedener Zwischenkulturen in einem Netzwerk von On-Farm-Versuchen. Agrarforschung Schweiz 6, 524-533.

Honegger, A., **Wittwer**, R., Hegglin, D., Oberholzer, H.-R., de Ferron, A., Jeanneret, P., van der Heijden, M., 2014. Auswirkungen langjähriger biologischer Landwirtschaft. Agrarforschung Schweiz 5, 44-51.

**Conference's contributions (selection)**

Common Annual meeting of the Soil Science Societies of Switzerland and Germany, 2019. Bern. Presentation (Excursion): *Langzeitversuch FAST: Einflüsse unterschiedlicher Bewirtschaftungs- und Bodenbearbeitungssysteme auf Bodeneigenschaften und Pflanzenentwicklung.*

XVe European Society of Agronomy Congress, 2018. Geneva, Switzerland.
Presentations: *The Potential of Cover Crops to Enhance the Sustainability of Arable Cropping Systems. / Resilience of Arable Cropping Systems Against Climate Change – Drought impacts.*

EGU General Assembly, 2018. Wien, Austria.
Presentation: *Impact of conventional, organic and conservation agriculture on soil functions and multifunctionality.*

5. Agroscope Nachhaltigkeitstagung, 2018. Zurich, Switzerland.
Presentation: *Bodenfunktionen und Multifunktionalität unter ÖLN-, biologischer und bodenkonservierender Bewirtschaftung.*

14. Wissenschaftstagung Ökologischer Landbau, 2017. Freising, Germany.
Presentation: *Die vielen Facetten von Zwischenfrüchten.* Poster: *Schneckenanfälligkeit von Zwischenfrüchten.*

13. Wissenschaftstagung Ökologischer Landbau, 2015. Eberswalde, Germany.
Poster: *Drohnenbilder zur Untersuchung von Pflanzenwachstum und Nährstoffdynamik.*

12. Wissenschaftstagung Ökologischer Landbau, 2013. Bonn, Germany.
Presentation: *Zwischenfrüchte als wichtiges Puzzleteil für den pfluglosen ökologischen Landbau.* Poster: *Wirtschaftlichkeit von pfluglosen Anbausystemen: Resultate für Winterweizen aus einem Anbauversuch.*

**Students co-supervised**

Valentin Theubet. 2014. MSc Thesis *"Weed infestation and population dynamics influenced by farming system, tillage and cover crops in a four year field trial in Switzerland."* ETH Zurich – Agroscope (with Prof. Dr. Achim Walter - Prof. Dr. Marcel van der Heijden).

Regula Good. 2015. MSc Thesis *"Impact of cover crop and tillage based systems on the abundance of arbuscular mycorrhizal fungi (AMF) and their contribution to P-uptake and yield."* University of Zurich – Agroscope. (with Prof. Dr. Pascal Niklaus - Prof. Dr. Marcel van der Heijden).

María Teresa Macías López. 2016. MSc Thesis *"Impact assessment of cover crops and tillage systems on the arbuscular mycorrhizal fungi and tomato"* University of Zurich – Agroscope. (with Prof. Dr. Pascal Niklaus - Prof. Dr. Marcel van der Heijden).

Emily M. Oliveira. 2017-2021. PhD Thesis *"Cropping systems´ responses to simulated summer drought: Understanding microbial contribution towards more sustainable practices."* ETH Zurich – Agroscope (with Prof. Dr. Nina Buchmann - Prof. Dr. Marcel van der Heijden).

**Teaching**

| | |
|---|---|
| 2013 - present | Grundlagen biologische Landwirtschaft und Hortikultur 3, teil Bioackerbau. Zürcher Hochschule für Angewandte Wissenschaft (ZHAW), Life Sciences und Facility Management (since 2015 course responsible). |
| 2019 – 2020 | Involvement in ETH seminar "Current aspects of nutrient cycles in agro-ecosystems". ETH Zurich, Institute of Agricultural Sciences. |
| 2018 | Guest presentation in ETH lecture "Soil biology". ETH Zurich, Department of Environmental Systems Science. |

**Professional experience**

| | |
|---|---|
| 2014 – present | Junior scientist and deputy group leader (0.75 FTE) at Agroscope, Research Division Agroecology and Environment, Plant-Soil Interactions group. |
| 2012 – 2014 | Junior scientist (1 FTE) at Agroscope, Institute for Sustainability Sciences, Ecological Farming Systems group (former Plant-Soil Interactions group). |

**Extension activities**

Several contributions to farmer courses organized by the extension services of Agridea and FiBL, 2014-2020. Switzerland

Yearly contributions to excursion of agricultural schools: School of Agricultural, Forest and Food Sciences (HAFL); Kompetenzzentrum für Bildung und Dienstleistungen in Land-, Lebensmittel- und Hauswirtschaft (Strickhof); Agricultural school of the Kanton Thurgau (Arenenberg)

**Public relations**

2019 Keystone-SDA (Swiss news agency) Video: Soil your undies initiative at Agroscope

2019 Keystone-SDA (Swiss news agency) Video: Greenhouse gas field measurement

2018 SRF Einstein (Science magazine). Rekordtrockenheit im Wasserschloss – die Folgen für die Schweiz. *https://www.srf.ch/play/tv/einstein/video/rekordtrockenheit-im-wasserschloss---die-folgen-fuer-die-schweiz?id=ab0ccd9b-f7d5-419d-89c9-3eddfd9e4040*

2018 SRF Tagesschau. Trockenheit in der Schweiz. *https://www.srf.ch/play/tv/tagesschau/video/trockenheit-in-der-schweiz?id=804a11af-415a-4dd8-acf0-3a1f6012e49c*